PACKAGE DESIGN FOR A LOW COST OPTICAL LIQUID LEVEL SENSOR

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PACKAGE DESIGN

FOR

A LOW COST OPTICAL LIQUID LEVEL

SENSOR

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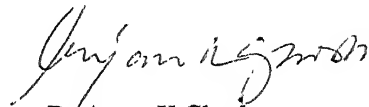to the

DEPARTMENT OF ELECTRICAL ENGEERING

I.I.T KANPUR

FEBURARY 1999

CERTIFICATE

It is certified that the work contained in the thesis entitled "PACKAGE DESIGN FOR A LOW COST OPTICAL LIQUID LEVEL SENSOR" by Major Navjot Singh Bedi, has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENTS

ABSTRACT

Sensors are also the key components in condition monitoring and measurement systems which are important for automation. Optical sensors are increasingly becoming popular over the conventional measuring devices due to the possibility of non contact methods of measurement and the ability to reach inacessible places when used in conjunction with optical fibres Sensors are also the key components in condition monitoring and measurement systems which are important for automation. There is a need for an optical sensor design and development in India. The optical sensor design has to be cost effective for it to be acceptable to the Indian market. We have anlysed various components of a low cost optical liquid level sensor using geometric optic and physical optic considerations and proposed a feasible design for the optical sensor. The detailed analysis of this sensor has been carried out in this thesis and guidelines for parameter selection have been evolved. The design guidelines of an optical liquid level sensor which uses an annular ring shaped detector has been proposed and its response has also been analysed in this thesis.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

A sensor is a device which converts a change in one physical parameter, into a change in the magnitude or phase of a second, different parameter, which can be measured more conveniently and perhaps more accurately [1] Sensors are used for measurement, detection, communication or provisioning of control signal to various parts or process of a system [2]

Condition monitoring and measurement systems are important for automation, which is critical in modern technology Sensors are key components in these systems As the push towards automation continues, the design and development of sensors is growing

1.1 Optical Sensors

Optical technologies have long played an important role in instrumentation and sensors, especially for non-contact measurements In an optical sensor, the information is passed from the physical /chemical variable being measured to an optical beam The changes in the characteristics of the optical beam are then determined Due to this structure, optical sensors have several advantages, which are listed in table 1 1

The optical sensors have enhanced and improved upon many existing applications, which are listed in table 1 2, and have also enabled some new applications to become possible One example of such a new application is monitoring the condition of critical structural parts such as bridge, trusses and aircraft skins Structures equipped with optical sensors to monitor their internal conditions during fabrication and operation are termed as smart structures and smart skins [2] Fig 1 1 illustrates schematically how an array of fibre optic gauges in an aircraft wing might provide a real time approximation to the actual strain distribution in the wing The goal of smart structure and smart skin research is to provide sufficient

information on conditions within critical structural systems so that corrective action can be taken in time to avoid a catastrophic failure such as rupture or buckling

In the developed nations of the world, optical sensor industry is a multi million dollar business and is projected to grow into a 560 million dollar industry by the turn of the century [3] Yet in India, optical sensors represent an emerging field. Most of the optical components are generally imported which makes them costly Thus, there is a need for optical sensor design and development The optical sensor design should be cost effective for it to be acceptable to the Indian market. Once a market for indigenous optical sensors is established we can think in terms of expensive optical sensors

In general optical sensors consist of (a) Optical Sources (b) Sensing elements through which/ in which the physical or chemical variables and optical fields interact (c) Photodetector (d) Electronic circuitry for signal processing and display [4] The components (a) - (d) are combined in a package

The performance of an optical sensor depends on the relative placement of all mechanical and electrical components into a package For an optical sensor desired to be cost effective and simple, it should comprise of the fewest possible number of optical components and a simple low cost package A package has many other roles in determining the overall performance of a sensor, such as

(a). **Alignment** The alignment of all optical, opto mechanical and opto electronic components and maintenance of the initial alignment throughout the life of the sensor is a critical aspect of packaging of optical sensors

(b). **Thermal Stability** Ensuring thermal stability of all components of an optical sensor is determined by the package design.

(c). **Shielding from Stray Radiation's** Shielding from both optical and RF or EMI radiation's, is done by the package, and the components inside the package are thus not affected by stray radiation's

(d). Spacing. Spacing between the source and detector needs to be maintained properly The focus of our attention in this thesis is how to select the interelement spacing in a sensor package We study the effect of spacing variation on the output of the sensor

While considering spacing, we take into account the relative importance of the size of the source and detector in the package and the overall arrangement of these items. We observe how the output of the sensor varies with parameters related to spacing and sizes and the arrangements

1.2 Overview of Research Work Done

A low cost optical liquid level sensor that can be easily fabricated has been proposed and the possible topologies to implement such a sensor have been analysed. The proposed sensor is simple in design and consists of only a source, a detector, a physical variable and a tubular package to keep everything in it This type of liquid level sensors can be used in the automobile industry, in the aeronautical industry and in measurement of the level of oil in electrical transformers (where electrical sensors can't be used)

The following design objectives have been looked at

(a) The relative importance of the size of the source and detector on the output of the sensor

(b) The effect of the variation in various dimensions of the package design, on the output of the sensor

(c) The effect of variation in the power and spot size of the beam emitted by the source, on the output of the sensor.

While carrying out the analysis of the optic sensor using geometric optics approach, it is assumed that a plane wave of light, coming from a point source falls on a plane mirror like liquid surface and undergoes reflection / refraction The transcendental equations relating the half acceptance angle, with other known parameters were derived for each topology, assuming that no side wall reflections take place We developed guidelines for parameter selection for the type of source, to be used in our set-up, given all other dimensions

The second approach followed in the analysis was based on wave propagation & diffraction The light beam was considered to be gaussian in nature, which is a reasonable approximation for a narrow, monochromatic, directional beam of light. The radius of curvature of the liquid surface in the sensor tube was incorporated in the calculations Using this analysis all the parameters related to spacing and size for the different arrangements were derived Lateral offset between the source and detector was also considered in the design where applicable We found that a reflective optical sensor arrangement with a source and an adjacent photodetector is the most practical for implementation in this design. In this design the coupling efficiency can vary between 6% to 14 % if the photodetector size is twice that of the source spot size In this type of a liquid level sensor there is a maxima in the coupling efficiency as the function of the liquid level We can carry out level measurements either in the lenar ranges before the maxima or after the maxima A design for an optical sensor which uses the annular (ring shaped) detector has been proposed and it is seen that there is no requirement of catering for an offset in such a detector This type of detector is also unaffected by misalignments caused due to a tilt in the tube

1.3 Overview of Thesis

In chapter 2, we have looked closely at optical sensors and the importance of package design The various types of optical sensors and their advantages have also been listed

Chapter 3 pertains to liquid level sensors and the need for such sensors has been touched upon. Various optical sensors for level sensing are also discussed The four possible topologies of our low cost simple optical sensor for liquid level measurement are discussed in this chapter

Chapter 4 deals with the geometric optics approach in the analysis of our optical sensor design and this analysis primarily helped in selection of the type of source to be used. As few inferences could be drawn from this approach, the analysis was done using the plane wave propagation approach

In chapter 5, the analysis of our optical sensor design has been carried out using wave propagation approach All the four proposed topologies of our low cost simple optical sensor for liquid measurement have been analysed and expressions for the spot size and power at the detector in each configuration have been derived In case of the reflective type of sensor configurations, the offset between the source and the detector has also been taken into account

Chapter 6 pertains to the analysis of all the four configurations of the optical sensor and selection of a feasible design for our low cost optical liquid level sensor Then using this feasible design which has been selected, further analysis of our optical sensor, using this feasible design, which has been selected is done A package design for an ' annular ring ' shaped detector base optical sensor is also proposed

In chapter 7, scope for further work has been elaborated & conclusions for the work done in the thesis have been drawn The scope for utilising the work done in this thesis, in fields other than liquid level sensing has also been touched upon.

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TABLE 1.1

ADVANTAGES OF OPTICAL SENSORS

1. Predominantly dielectric construction so it can be used in high voltage , electrically noisy, high temperature , corrosive and other stressing environments   Also , immunity of the signal to EMI / RFI

2. Highly reliable and safe with no risk of arcing

3. No residual capacitive or inductive effect

4. Small size and weight

5. Allows access to normally inaccessible areas when used in conjunction with optical fibres

6. Remote sensing is possible when used in conjunction with optical fibres

TABLE 1.2

TECHNOLOGICAL APPLICATIONS ENHANCED BY USE OF OPTICAL SENSORS

1. Anti burglar alarm systems

2. Intra board communication between various IC's in the motherboard of a PC

3. Various kinds of level sensors in automobiles and aircraft's

4. Defence applications (for e g SMART bombs that continuously sense the height above the ground and detonate at a specified height)

5. In feedback loop and control system applications

6. Fire and smoke alarm systems

7. In automated production to sense position thickness and to count the number of finished products on the conveyor belt

8. To sense rotation in aerospace and military applications
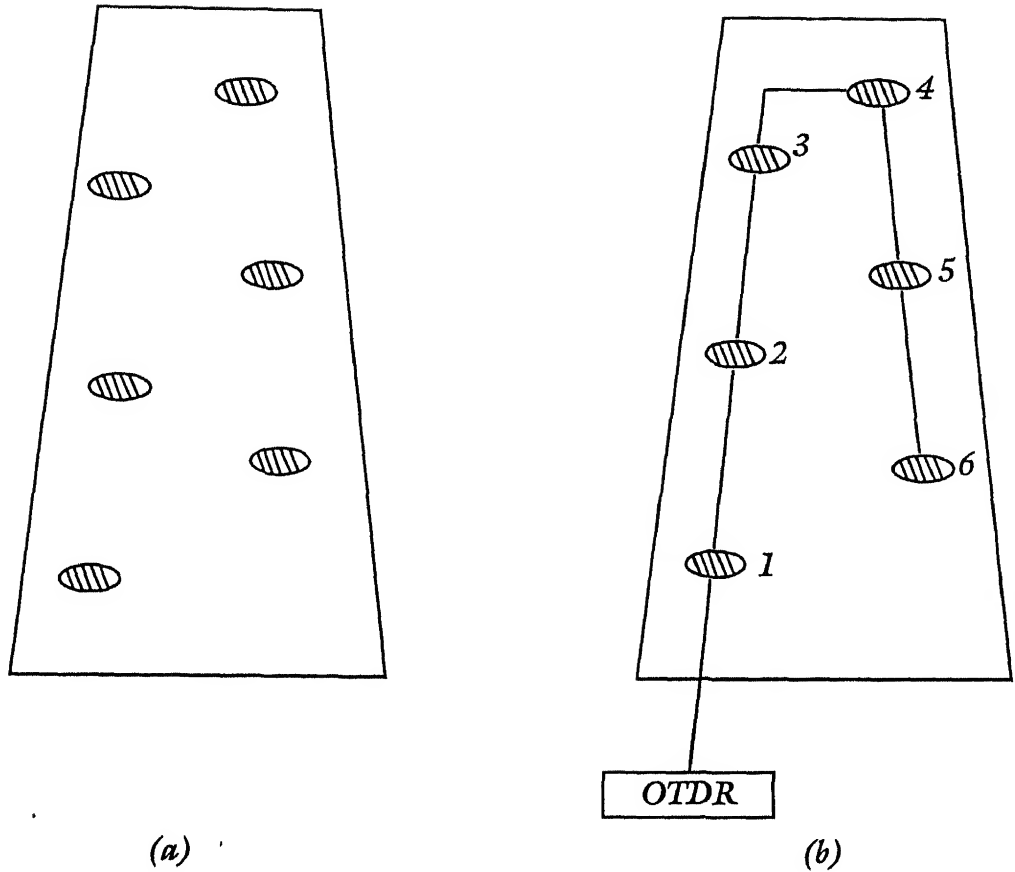
Fig. 1.1   (a) Air Craft wing with 6 strain gauges distributed
            over its cross - section
           (b) Connection of fiber optic strain sensors in wing to
            OTDR (optical time donain refractometer) using
            time multiplexing

CHAPTER 2

OPTICAL SENSORS

In this chapter we take a close look at optical sensors including their advantages and their classification into various categories The package design and the approach followed in selecting our low cost optical sensor have also been touched upon The major issues associated with the design have also been highlighted

2.1 Types of Optical Sensors

Broadly, optical sensors may be classified under the following three categories

(a). Free Space Optical Sensor. In this sensor the light beam, which interacts with the sensing head, propagates in air / free space

(b). Optical Fibre Sensor In this type of sensor, fibres are used to convey light from the source to the sensor head or the sensing variable acts on the fibre changing the properties of the fibre The fibre can be sensitised to a large number of measurands like temperature, strain etc and several varieties of optical fibre sensors are available commercially

(c). Integrated Fibre Optic Sensors. These are mostly integrated versions of the fibre optic sensors They are deployed when small size (mm - micron) and high sensitivities are required, they may be more expensive than the free space optical sensors & the fibre optic sensors [1]

Optical sensors can also be classified on the variety of different mechanisms to turn a change in the measurand into a change in the optical power output of the guided wave optical circuit, which is then sent to a photodetector and processed automatically [2] The various types of optical sensors may thus be classified as under

(a). Intensity Modulated Sensors The measurand directly changes the intensity of an optical beam transmitted through the sensor Shown in fig 2 1 is one such sensor where the intensity of

8

liquid.

(b). Phase Modulated (Interferometeric) Sensors. In this type of sensor, the measurand causes a phase shift in the incident beam of light or a change in the polarisation of the incident beam that is interfered / compared with a reference beam Then the shift in phase /polarisation is converted to the variation in output intensity of the optical circuit. Aschematic of this type of sensor is as shown in fig 2 2

2.2 Package Design for an Optical Sensor

One of the technical problems that have to be solved for manufacturing and deploying an optical sensor is that of sensor packaging In all types of sensor designs, packaging is an important issue, but in non-optical cases it is comparatively less significant. The major roles of a package of an optical sensor as already explained in chapter 1 are alignment, thermal stability, shielding from stray radiation's and proper spacing between the various components In this thesis we have considered the package design for a simple low-cost optical sensor The requirement of it being low cost meant that the design of the optical sensor should have only a few components The optical sensor would comprise of the basic components of a source, a detector, a physical variable and a device to keep it in. We selected liquid level measurement to analyse the packaging of a source and detector as liquid level is a physical variable that could be incorporated in our analysis of package design at no additional cost and also for the reason that few automobile & aeronautical concerns had shown an interest in the feasibility of an optical sensor for liquid level measurement A laser diode or an LED or a fibre illuminator (tips of fibre bundle) may be used as a source in our sensor The receiving device may either be a PIN photodiode (for in situ measurement) or an optical fibre or fibre bundle for transmitting the signal to a remote distance

The intensity modulated optical sensors are the simplest and most widely used in the field of optical sensors [3] Thus for the analysis of our package design, we chose an intensity modulated optical sensor Starting from a simple design, we kept on modifying the package design to take into account various intricacies that this simple design projected.

9

The first issue that we had to decide on was the shape of the package & the package design that we have considered is housed in a hollow cylindrical package Then while deciding on the design for a simple intensity modulated liquid level sensor, we had the option to either go in for a reflective type of sensor or for a refractive type of sensor and we decided to do an analysis of both these types of sensors using geometric optic considerations, and then select a feasible design

Having decided on the shape of the package and the type of optical sensor to be used, we had to select the type of source to be used (i e LED Laser Diode or fibre illuminator) This selection was done based on the divergence angle of the source Thus, based on the tentative dimensions of the package, we developed guidelines for parameter selection for the type of source and also evolved a relationship between the under mentioned variables

(a) Beam spot size

(b) Beam divergence angle

(c) Height & radius of base of cylindrical package

(d) Detector size

(e) Surface tension, density contact angle & refractive index

Once the type of source was decided upon, a fresh analysis was carried out using wave propagation approach The radius of curvature of the liquid surface was expressed in terms of other known parameters of the package and was taken into account while carrying out the wave propagation analysis

Such an analysis was carried out for both the reflective and refractive type of optical sensors and two configurations of each type were considered Subsequently a comparative analysis of these results was carried out and sensor configurations no 3 was selected as it appeared to be a feasible option. In this sensor, as shown in fig 2 3, both the source and the detector are on top of the tube containing the liquid.

The offset, which exists between the source and detector in reflective type of sensors, was also considered and incorporated in the analysis of these sensor configurations

Also, a prototype design for an " annular ring shaped detector " based optic sensor was proposed, which eliminated the lateral offset between source and detector The analysis of a sensor with an annular ring shaped detector was also carried out

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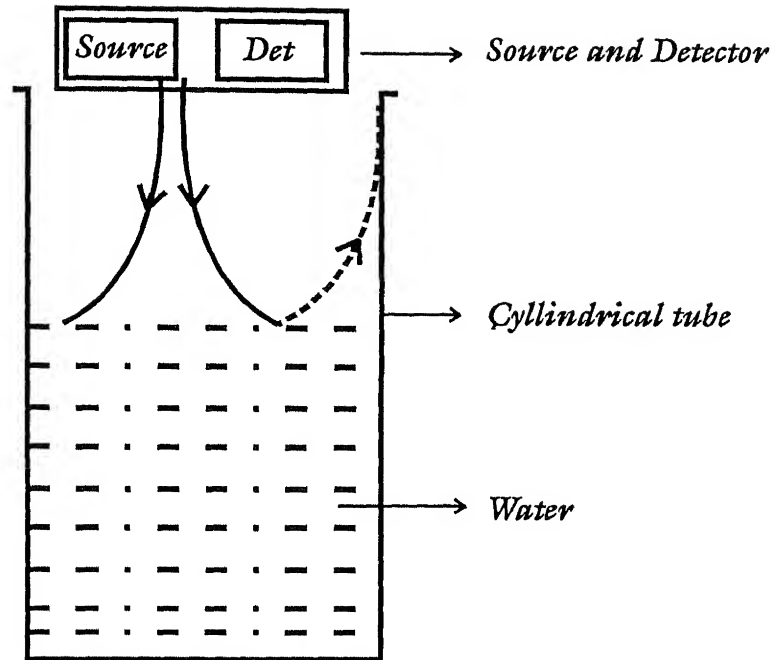
Fig. 2.1   A Simple intensity modulated optical sensor
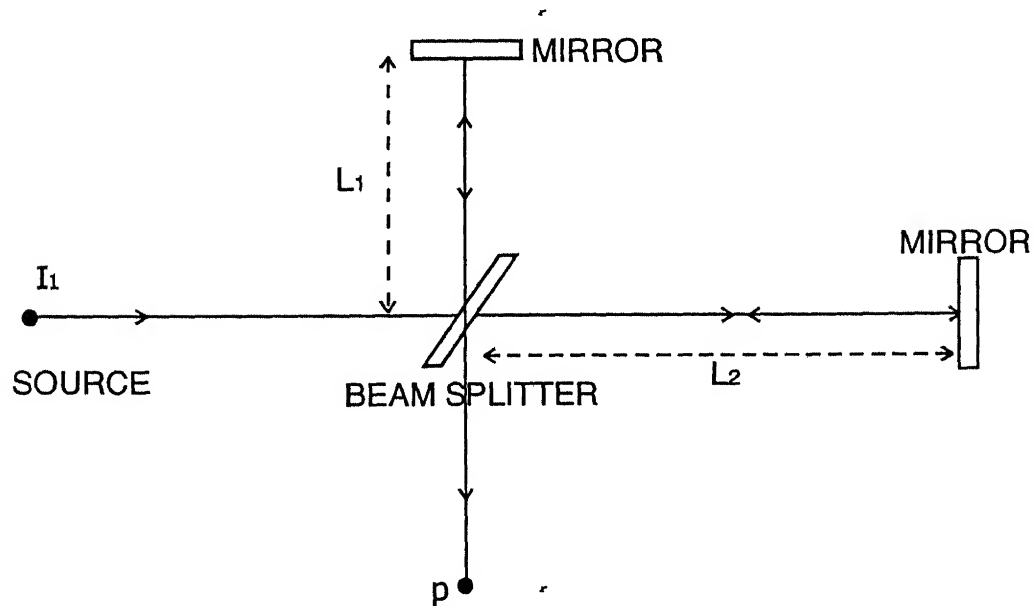
*Fig. 2.2   A Michelson Interferometer realized with conventional
bulk optic components.*

CHAPTER 3

LIQUID LEVEL SENSORS

We selected liquid level measurement to analyse the packaging of a source and detector as liquid level is a physical variable that can be measured with no additional transducer The liquid surface and /or the bulk of the liquid interacted with the light beam changing its intensity as the height of the column varied. Also we did not find such simple liquid level sensors reported in literature

3.1 Various Types of Liquid Level Sensors.

Liquid level is an important variable that is measured in aircraft's process industries and many other areas using various kinds of sensor These technologies are based on floats, capacitive sensors, ultrasound and nuclear radiation techniques [1] These technologies are

(a). Float. As shown in Fig (3 1). a plastic air filled ball is hinged to the top of the vessel containing the liquid. the ball floats on top of the liquid surface A pointer is attached at the other end of the device holding the ball The pointer moves along a calibrated scale indicating the liquid level When the liquid level is low the ball floats on top of the liquid but at a low level as shown in Fig 3 1 (a), and the pointer indicates a low level As the liquid level increases, the ball rises and the pointer attached to the other end of the rod moves towards the " full "(maximum) level indicator This type of liquid level sensor is easy to make and it is widely used. It is a low cost device but its accuracy is not high.

(b). Capacitive Type A schematic diagram of this type of sensor is shown in Fig (3 2) A cylinder is introduced in the middle of a tank containing the liquid. If ' d ' is the separation between the positively and negatively charged plates, ' A' is the surface area and 'ε' is the permitivity of the liquid, then the capacitance 'C' is given by $C = \varepsilon A / d$. A and d being constants, C is directly proportional to ε and the value of ε can be mapped on to the liquid level. Thus 'C ' is proportional to liquid level and can accordingly be calibrated.

This type of sensor is used in aeronautical and automobile industry Its main advantage is that this technology is widely accepted and it can be manufactured easily However, the change in capacitance due to the change in the value of ε is usually small and thus we are only able to monitor the liquid level using complex electronics if we want accurate   results   Also, the presence of a number of wires to and from the sensor, are a potential source of fire hazard, especially in confined spaces like aircraft's Due to this reason the measurement of capacitance also changes

(c). Ultrasound Sensors. As shown in Fig (3 3) ultrasound waves are emitted from a source strike the surface of the liquid and get reflected back to the sensor where they are detected. The time interval between emission and receipt of the signal is directly dependent on the distance between the ultrasound source and the surface of the liquid This time interval is mapped on to the liquid level and measurement is done This type of sensor is widely used in marine applications by ships to know the depth of   water at a particular spot and is accurate

(d). Optical Liquid Level Sensor The optical liquid level sensors are mainly intensity modulated sensors A number of optical sensors have been reported. Most of these are fibre optic sensors based on differential absorption [2] bending induced mode coupling [3] [4] and index dependent total internal reflection [5] These sensors are suitable for measurement of discrete liquid levels Continuos sensors have been designed on the principles of optical radar [6] and index induced waveguide coupling at a liquid surface [7] These can be classified under the following categories

As shown in Fig (3 4), in this type of sensor, fibres are used to convey light from the source to the sensor head After being reflected from the liquid surface, the light is conveyed back to the detector through a fibre These   types of sensors are good and can be used to access inaccessible areas

3.2 A Simple Optic Liquid Level Sensor for a Case Study in Package Design

For a case study in package design we chose a free space optical sensor that can measure the liquid level continuously We put the liquid whoose level is to be measured in a cylindrical container and bring an optical source and a photodetector in the proximity such that the intensity of the light falling on the photodetector is changed by a refraction through the liquid column or by a reflection from the liquid surface In Fig (3 5), we show one possibleconfiguration with source and detector are placed on top and bottom respectively of the tube containing the liquid. This type of level sensor is easy to implement. Due to its inherently dielectric construction, there is no risk of arcing and thus this sensor can be used for measurements in a hazardous environment Thus this sensor overcomes the disadvantages of the capacitate type of sensor Also, this type of sensor can be used to measure the curvature of the liquid surface

There are four different ways in which a source and a detector can be arranged, to design a this type of simple low cost optical liquid level sensor The first arrangement is shown in Fig (3.5) In the second arrangement, the detector is kept at the top of the tube containing the liquid and the source is at the bottom of the tube This topology will hereafter be refereed to as "Sensor Configuration No 2" and the same is shown in Fig (3 6) In the third arrangement, both the source and detector are kept at the top of the tube containing the liquid. This topology will hereafter be refereed to as "Sensor Configuration No 3" and the same is shown in Fig (3 7) In the last arrangement, both the source and detector are kept at the bottom of the tube This topology will now be refereed to as "Sensor Configuration No 4" and the same is shown in Fig (3 8)

Of these four topologies listed above, the first two are examples of transmissive type and are intrinsic type of intensity modulated sensors The first two, that is Configuration no's 3 and 4, are transmissive type and are intrinsic type of intensity modulated sensors.

Even for these simple structures we need to select the type of source to be used, the type of the detector required, the tube height and diameter and the separation between the source and detector to

package the optical sensor. In addition to these package design parameters, it is also necessary to select the range of optical power incident from the source, the wavelength at which the source is required to operate and the minimum spot size of the gaussian beam at that wavelength. We studied the selection of parameters using both geometric optic analysis and wave propagation considerations. The geometric optic analysis provided us with guidelines for parameter selection and helped in the selection of the type of source to be used for the optical sensor. However, a detailed analysis of these simple structures was possible using wave propagation considerations.

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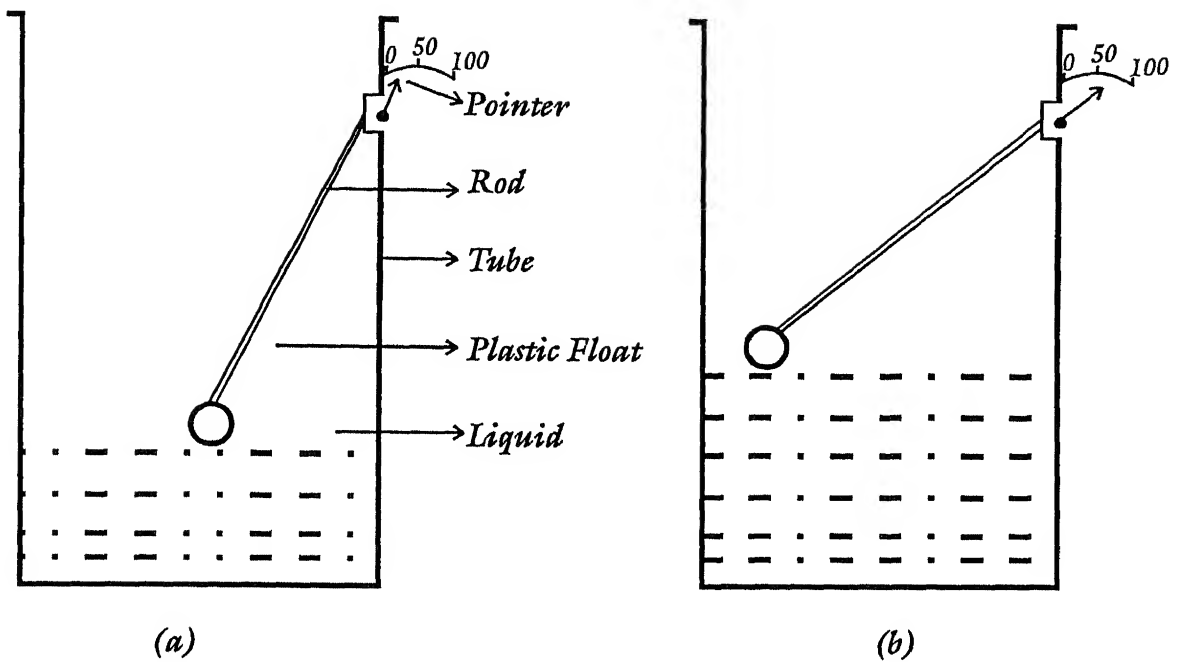
Fig. 3.1   (a) Float indicating less level of liquid
(b) Float indicating liquid level nearly at half way mark
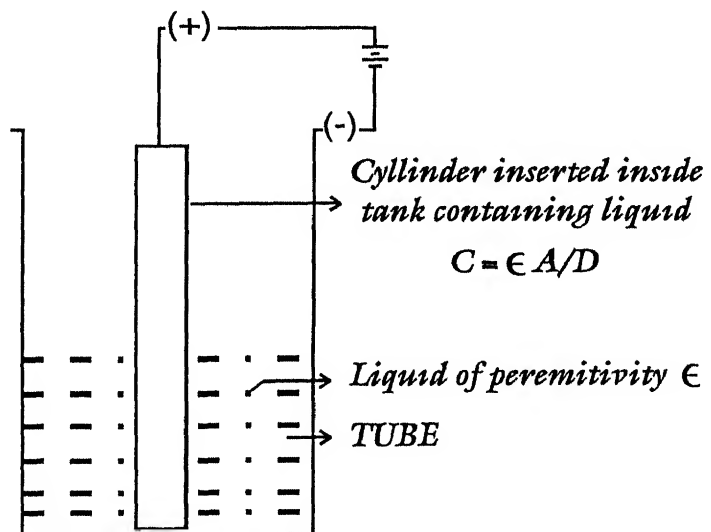
Fig. 3.2   Capacitive type of liquid level sensor
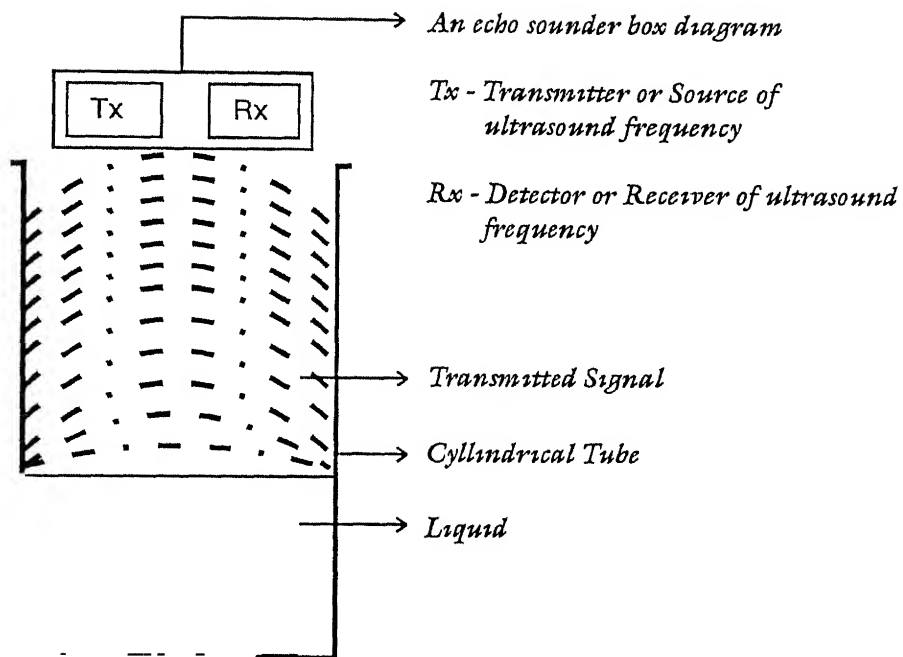
Fig. 3.3 An Ultrasound Liquid Level Sensor

An echo sounder box diagram

Tx - Transmitter or Source of ultrasound frequency

Rx - Detector or Receiver of ultrasound frequency

Transmitted Signal

Cyllindrical Tube
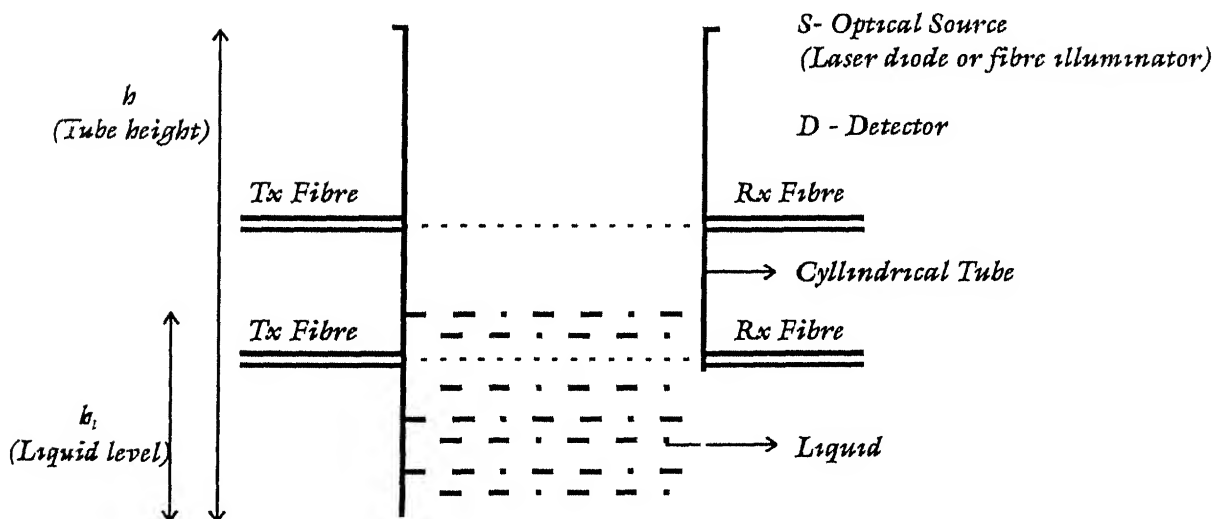
Liquid

Fig. 3.4 A Fibre Optic Liquid Level Sensor

h (Tube height)

h_l (Liquid level)

Tx Fibre

Tx Fibre

Rx Fibre

Rx Fibre

S- Optical Source (Laser diode or fibre illuminator)

D - Detector

Cyllindrical Tube

Liquid

LEGEND

1 h = height of tube
2 $h-h_1$ = Air column length
3 h_l = height of liquid column
4. h_o = distance of LD from the top of the tube

Fig. 3.5 Sensor configuration No. 1

LEGEND

1 $(h-h_l)$ = length of Air column
2. h_o = distance of LD from tube base
3 w = width / dia of tube

Fig. 3.6 Sensor configuration No. 2

LEGEND
1. h = height of tube
2. $h - h_1$ = Air column length
3. h_1 = height of liquid column

Tube

Liquid

Fig. 3.7 Sensor configuration No. 3

LEGEND
1. $(h - h_1)$ = length of Air column
2. h_1 = height of liquid column
3. w = width / dia of tube

Tube

Liquid

Fig. 3.8 Sensor configuration No. 4

CHAPTER 4

GEOMETRIC OPTICS APPROACH FOR STUDY OF OPTICAL
LIQUID LEVEL SENSOR ARCHITECTURE

Geometric optics or ray optics is a simple way of describing the behaviour of light We first study the optical liquid level sensor architectures using ray optics to derive design guidelines The four possible configurations of our low cost liquid level sensor are as shown in fig 4 1 Fig 4 1(a)and(b) pertain to the transmissive type of optical sensor , in which the source or detector is at the top of the tube respectively One important consideration in the design was that there should be no multiple ray paths from the source to the photo detector owing to the reflection of rays from the sidewalls of the tube If multiple rays reached the photo detector then it would be difficult for the photo detector to discern which ray is incident upon it directly and which ray arrives after being reflected from the sidewalls of the tube There is also a possibility that the ray which is directly incident on the photo detector and a ray which reaches photo detector after being reflected from the side walls, arrive at the photo detector at the same time In such an instance both these rays will add up and the effect of any one beam will not be seen

4.1 Data Used For Generation of Results

Based on geometric optics we will analyse all the four configurations and establish a relationship between the various physical parameters of each sensor An idea about the beam divergence angle of a source (LED, Laser Diode or Fibre illuminator) can be obtained from the geometric optic analysis We thus try to calculate the maximum value of the half divergence angle, in each of the four topologies discussed in chapter 3, in order to get an idea of the acceptable limit of the beam divergence angle and thus decide upon the type of source to be used for our optical sensor

Having established a relationship between the various physical parameters of each sensor and the beam divergence angle of a source in all the four configurations, programmes are written to evaluate its value The programmes can be run by any user by inputting various values of design parameters such as tube height h, tube width w and refractive index of liquid n_2 The values of all these parameters had to be selected to suit the specifications of our low cost optical sensor

There is a requirement of an optical window to be put on the base of the tube for transmissive type of sensors (sensor configuration No's 1 and 2) Optical windows come in specified sizes and due to the complexity in their fabrication process, their cost increases as their size becomes larger For our low cost optical sensor, the optical window should be large enough to accommodate the source and detector Thus an optical window with a diameter of approximately an inch (25 4 mm) would suffice for our purpose Keeping a margin of 1 2 mm on either side of the diameter to allow for fixing the optical window to the walls of the tube, at the base of the tube we are left with an optical window with a diameter of 23 mm

The tube in which the liquid is kept though should not be so long that it becomes unwieldy to handle, yet it should be long enough to allow proper measurement of the liquid level by our optical sensor In view of this, a tube of length = 10 cm (100 mm) would meet the requirement Moreover, the range over which the sensor should be able to function should be starting from 5 mm from the base of the tube to 10 mm short of the top of tube In view of this , a tube of length = 11 5cm (115 mm) would meet the requirement as this would allow measurement to be done over a range of 10 cm (100 mm) Moreover , HAL private communications limited had also projected the requirement that the liquid measurement should be possible over a length of 10 cm The liquid selected for the purpose of our analysis is water and the refractive index of 1 33 has been accordingly selected The values of various parameters thus chosen to find the value of ' half beam divergence angle ', for various values of liquid level are as listed below

    (a) Diameter of tube   23 mm

    (b) Height of tube   115 mm

    (c) Refractive index of liquid   1 33

4.2 Beam Divergence Angle

An idea about the beam divergence angle of a source (LED ,Laser Diode or Fibre illuminator), can be obtained from the geometric optic analysis We thus try to calculate the maximum value of the half

divergence angle, in each of the four topologies discussed in chapter 3, in order to get an idea of the acceptable limit of the beam divergence angle and thus decide upon the type of source to be used for our optical sensor

In the course of this analysis we make the following assumptions -

(a) The source and detector are placed at the centre of the tube containing liquid in order to ensure that the half divergence angles on either side of the centre of tube are same and is equal to half of that of the actual divergence angle of the source

(b) Reflectivity of the surface is 100 %

(c) The beam emitted by the point source is lambertian in nature, so as to be able to use the value of the divergence angle to calculate the intensity received by detector

(d) The reflecting surface is much larger than the wavelength of the light.

(e) Diameter of the source and detector is much smaller than the distance between the source/ detector and reflecting surface

4.3 Half Divergence Angle Relationships and Results

In order to ensure that no sidewall reflections take place, the source and detector were placed in the centre of the tube Also, assuming that the most divergent ray emitted by the source would land at the edge of the base of the tube, the half divergence angle was calculated Given in the subsequent paragraphs, is the analysis of each of the four possible architectures of our liquid level sensor

4 3.1 **Analysis of Sensor Configuration No 1:** In this configuration as shown in fig 4 1, the source is at the top of the tube of height 'h' filled upto a height 'h_1', with a liquid of refractive index n_2 The equation relating the value of half divergence angle (hereafter referred to as HDA) θ with the other parameters is

$$\theta = \text{Sin}^{-1} \left\{ (n_2/n_1)\,(w - b\tan\theta)\,/\,(2\,h_1\,\sqrt{1 + (\frac{w - b\tan\theta}{2h_1})^2}\,\right\} \qquad (4\ 1)$$

where, n_1 = refractive index of air =1, n_2 = refractive index of liquid. h_1 = height of liquid column from base of tube .b= h_o +h -h_1 , h_o = distance of laser diode from top of tube ,h =height of tube ,w= width of tube

Rearranging equation 4 1 and rewriting we get a transcendental equation in tan θ as under

$$\tan^2\theta\,(\,b^2\,(1\text{-}a^2)\,) + \tan^3\theta\,(\,2w\,b\,(a^2\text{-}1)\,) \quad + \tan^2\theta\,(\,c^2 + w^2 - a^2\,(w^2 + b^2)\,) \,+$$

$$\tan\theta\,(\,2\,w\,b\,a^2\,) \,-\, a^2\,w^2 \,=\, 0 \qquad\qquad (4\ 2)$$

where $a = n_2/n_1$ and $c = 2\,h_1$

Evaluating equation (4 2) using Newton Raphson method [3] , we get the value of θ for various combinations of the values of h_o and h_1 , such that no side wall reflections take place , and these are listed in Table 4 1 These values of 'θ ' were obtained for the test data before The liquid level (h_1) was varied from 0 mm, 10 mm, 50 mm , 100 mm and 115 mm and the offset or distance of source from the top of the tube (h_o) was varied from 0 mm to 5 mm in steps of 1 mm This same test data has been used during the analysis of the other optical sensor topologies, which are explained in this section.

4.3.2 Analysis of Sensor Configuration No 2 : In this configuration as shown in fig 4 2 , the detector is at the top of the tube of height 'h' filled upto a height 'h_1 ' ,with a liquid of refractive index n_2 The desired transcendental equation relating θ with other physical parameters is given by

$$\tan^2\theta\,(\,p^2\,(a^2\text{-}1) + a^4\,) - p^2 \,=\, 0 \qquad\qquad (4\ 3)$$

where,

$$p^2 = (\,w^2\,k_5 + k_2\,b^4 + k_3\,b^2 + k_4\,\sqrt{k_5}\,b^2 - 4wbh_o\,k_5 - 4wbh_1\,\sqrt{k_5}\,)\,(1/(k_5\,k_6))$$

where a= n_2/n_1 , and the constants $k_1, k_2, k_3, k_4, k_5, k_6$ are mathematical expressions relating the variables and constants pertaining to the dimensions of the tube and to the liquid ,for ease of computation Solving equation 4 3 by Newton Raphson method and using the same test data as was used for the

analysis of optical sensor configuration No 1, we get the value of θ for various combinations of the values of h_o and h_1 , such that no side wall reflections take place , and these are listed at Table 4 2

4.3.3 Analysis of Sensor Configuration No 3.

In this configuration as shown in fig 4 3 , both the source and detector are at the top of the tube of height 'h' filled upto a height 'h_1' ,with a liquid of refractive index n_2 The desired transcendental equation relating θ with other physical parameters is given by

$$k_3 \tan^4 \theta + k_4 \tan^2 \theta + k_5 \sqrt{k_7} \tan\theta - k_6 = 0 \qquad (4 4)$$

where the constants $k_1, k_2, k_3, k_4, k_5, k_6$ and k_7 are mathematical expressions relating the variables and constants pertaining to the dimensions of the tube and to the liquid ,for ease of computation and the symbols h_o and n_1 have meaning as explained in section 4 2 (a)

Solving equation 4 4 by Newton Raphson method and using the same test data as was used for the analysis of optical sensor configuration No 1, we get the value of θ for various combinations of the values of h_o and h_1 , such that no side wall reflections take place , and the same are listed at Table 4 3

4.3.4 Analysis of Sensor Configuration No 4.

In this configuration as shown in fig 4 4 , both the source and detector are at the base of the tube of height 'h' filled upto a height 'h_1' ,with a liquid of refractive index n_2 The desired transcendental equation relating θ with other physical parameters is given by

$$k_3 \tan^2\theta (k_1 - 4 h_o^2) - 8h_o h_1 \sqrt{k_3} \tan^2 \theta - 4 h_1^2 \tan^2\theta + 4wh_o k_3 \tan\theta +$$

$$4wh_1 \sqrt{k_3} \tan\theta - k_3 w^2 = 0 \qquad (4 5)$$

where the constants k_1 , k_2 and k_3 are mathematical expressions relating the variables and constants pertaining to the dimensions of the tube and to the liquid ,for ease of computation and the symbols h_o and n_1 have meaning as explained in section 4 2(a)

Solving equation 4 5 by 'Newton Raphson ' method and using the same test data as was used for the analysis of optical sensor configuration No 1, we get the value of θ for various combinations of the values of h_o and h_1, such that no side wall reflections take place, and the same are listed at Table 4 4

4.4 Comparative Analysis

A comparative analysis of the results obtained from all the 4 topologies is tabulated as under For each optical sensor configuration, for a particular combination of the offset (h_o) and the liquid level (h_1), there is a smallest value of half maximum divergence angle (HMDA) that is θ small hereafter abbreviated as θs, and a largest value of HMDA that is θ large hereafter abbreviated as $\theta 1$ The values of θs and $\theta 1$ (in degrees) for each of the four architectures, for the test data listed in section 4 1(a) of this chapter, is listed at table 4 5

It was observed that for all four cases analysed, $\theta 1$ always occurred when the offset (h_o) is the smallest of the 5 values over which it is varied and the liquid level (h_1) is the largest of the values over which it is varied, that is from '0' to 'h' Also, θs always occurred when ' h_o ' is the largest of the 5 values over which it is varied and ' h_1 ' is the largest of the values over which it is varied

4.5 Parameter Selection and Type of Source

The reasons for selecting the values of the tube length, tube diameter and refractive index of the liquid have already been explained in section 4 1 of this chapter and the values of these three parameters are 115mm, 23mm and 1 33 respectively The HDA of a light cone emitted by the source was calculated for a tube having a height = 115 mm and radius = 11 5 mm, and the results are tabulated as per table's 4 1 - 4 4 On analysis of the results it was found that the laser diode would be a suitable choice for the source as it's divergence angle is in 'milli radians ' and it meets the requirements of the values of HMDA calculated for the four topologies being considered for an optical sensor

An LED can be used as a source , but a source generating a coherent and directional beam of light would , be better in performance to an LED and as such the laser diode was found to be an appropriate choice for the source

The relationship developed between the HMDA ' θ ' , the height of the tube 'h' ,the tube diameter ' w ' and the height of liquid level ' h_1 ' as listed in equations 4 2 to 4 5 , can also be used for parameter selection by the package designer / manufacturer of the optical sensor as any one of the parameters can be expressed in terms of the other parameters

An idea about the shape of the vessel in which the liquid should be kept in order to minimise sidewall reflections ,can also be made For example, for sensor configuration No 3 (in which both the laser diode and detector are on top of the tube) , a tube whose diameter increases gradually on going from top towards the bottom , would be ideally suited to minimise the occurrence of side wall reflections However , a more detailed analysis about this aspect could be done subsequently

4.6 Summary

Using the ' Geometric Optics Approach ' to carry out the analysis of the four possible topologies of our low cost optical sensor ,it was found that the laser diode would be a suitable choice for the source of the low cost optical sensor (LCOS) A set of values of the tube parameters for our low cost optical sensor , have also been selected A feasible shape of the tube in which the liquid is to be kept has also been proposed However , in order to do a more detailed analysis and obtain further information about various design parameters , the wave propagation analysis was carried out and the same is available in the next chapter of this thesis

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3   Saul Teukolsky , William Vetterling et al , " Numerical Recipies in C, The Art of Scientific Computing", Cambridge Unniversity Press , London

4   Matlab User Manual - Student Edition, Mathwork Inc, U S.A, 1994

TABLE 4 1

Values of θ (in degrees) for various combinations of the values of h_o and h_1 for Sensor Configuration No1

$h_o \downarrow h_1$ -0 mm	10 mm	50 mm	100 mm	115 mm
0 5 7106	5 8365	6 4021	7 2879	7 6048
1 5 6619	5 7854	6 3406	7 2081	7 5179
2 5 6137	5 7352	6 2803	7 1031	7 4330
3 5 5664	5 6859	6 2211	7 0538	7 3499
4 5 5199	5 6374	6 1630	6 9790	7 2687
5 5 4742	5 5897	6 1060	6 9059	7 1893

TABLE 4 2

Values of θ (in degrees) for various combinations of the values of h_o and h_1 for Sensor Configuration No 2

$h_o \downarrow h_1$ --- 0mm	10 mm	50 mm	100 mm	115 mm
0 3 2247	3 3934	4 2923	6 4401	7 5133
1 3 2091	3 3761	4 2648	6 3782	7 4285
2 3 1937	3 3590	4 2376	6 3175	7 3456
3 3 1784	3 3421	4 2108	6 2579	7 2646
4 3 1632	3 3254	4 1843	6 1994	7 1853
5 3 1482	3 3088	4 1582	6 1420	7 0954

TABLE 4 3

Values of θ (in degrees) for various combinations of the values of h_o and h_1 for Sensor Configuration No 3

$h_o \downarrow h_1$ ---	0 mm	10 mm	50 mm	100 mm	115 mm
0	0 0249	0 0299	0 0776	1 2541	6 7687
1	0 0245	0 0293	0 0753	1 1218	6 7558
2	0 0241	0 0288	0 0731	1 0085	6 5883
3	0 0237	0 0282	0 0710	0 9110	6 1237
4	0 0233	0 0277	0 0689	0 8264	5 4725
5	0 0229	0 0272	0 670	0 7528	4 8720

TABLE 4 4

Values of θ (in degrees) for various combinations of the values of h_o and h_1 for Sensor Configuration No 4

$h_o \downarrow h_1$ ---	0 mm	10 mm	50 mm	100 mm	115 mm
0	5 7106	5 8365	6 4021	7 2878	7 6048
1	5 6617	5 7854	6 3406	7 2082	7 5180
2	5 6136	5 7352	6 2803	7 1300	7 4331
3	5 5663	5 6859	6 2211	7 0540	7 3498
4	5 5198	5 6374	6 1631	6 9990	7 2689
5	5 4741	5 5891	6 1061	6 9060	7 1895

TABLE 4.5

The values of θs and θ1 (in degrees) for each of the four Configurations

	Sensor Configuration No			
	No 1	No 2	No 3	No 4
θs and θ1	5 4742	3 1482	0 0229	5 4741
θs and θ1	7 6048	7 5133	6 7687	7 6048

where θs is the smallest value of half maximum divergence angle (HMDA), and θ1 is the largest value of HMDA
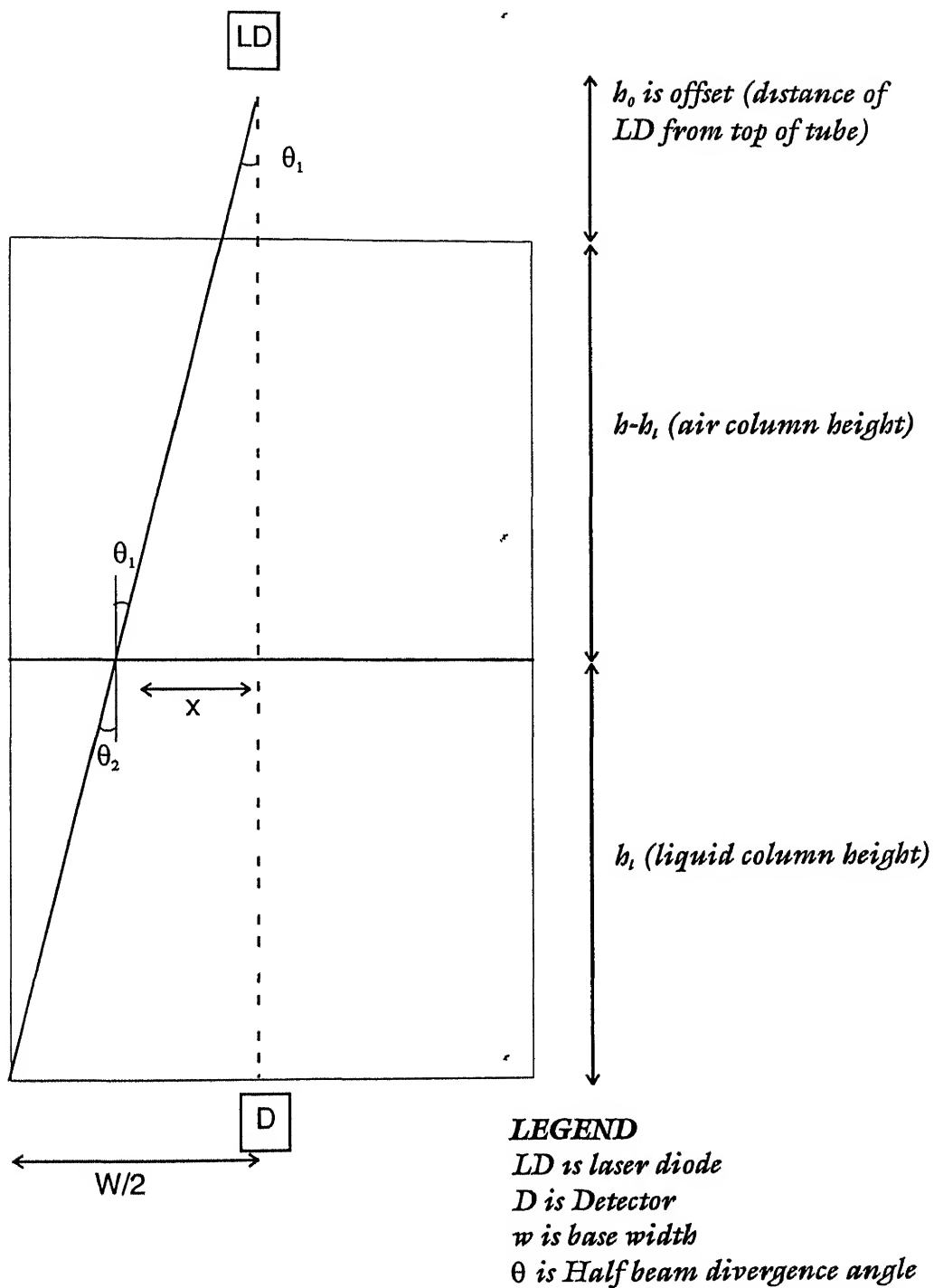
FIG. 4.1 ANALYSIS OF CONFIGURATION NO.1

$w/2$

$w/2-x$ x

D

n_1

θ_3

x_3 x_1

θ_2

n_1

θ_3

x_1

θ_1

LD

$b-b_1$

b

b_1

b_o

**FIG. 4.2 ANALYSIS OF CONFIGURATION NO.2
(LD AT BOTTOM & DETECTOR AT TOP)**

LD/Det

S

b_o

$b-b_l$

n_1

θ_1

n_2

θ_2

b_l

θ_4

W/2
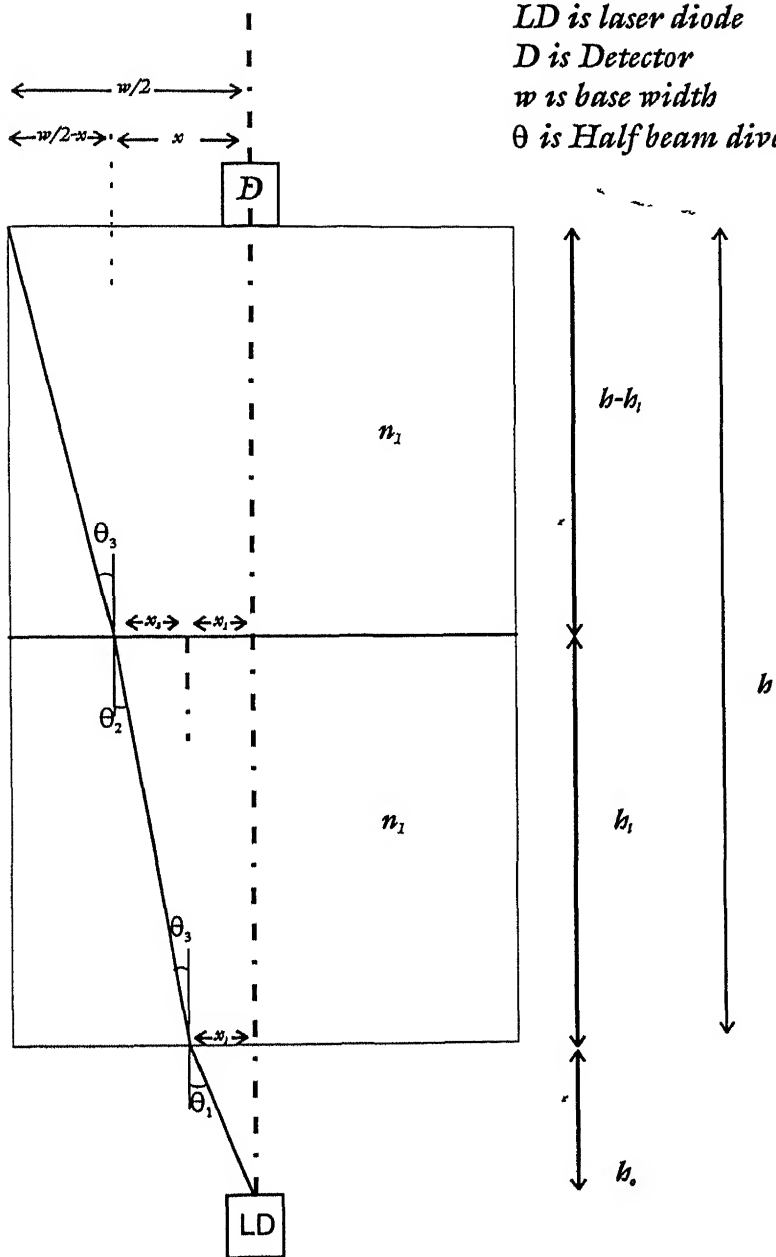
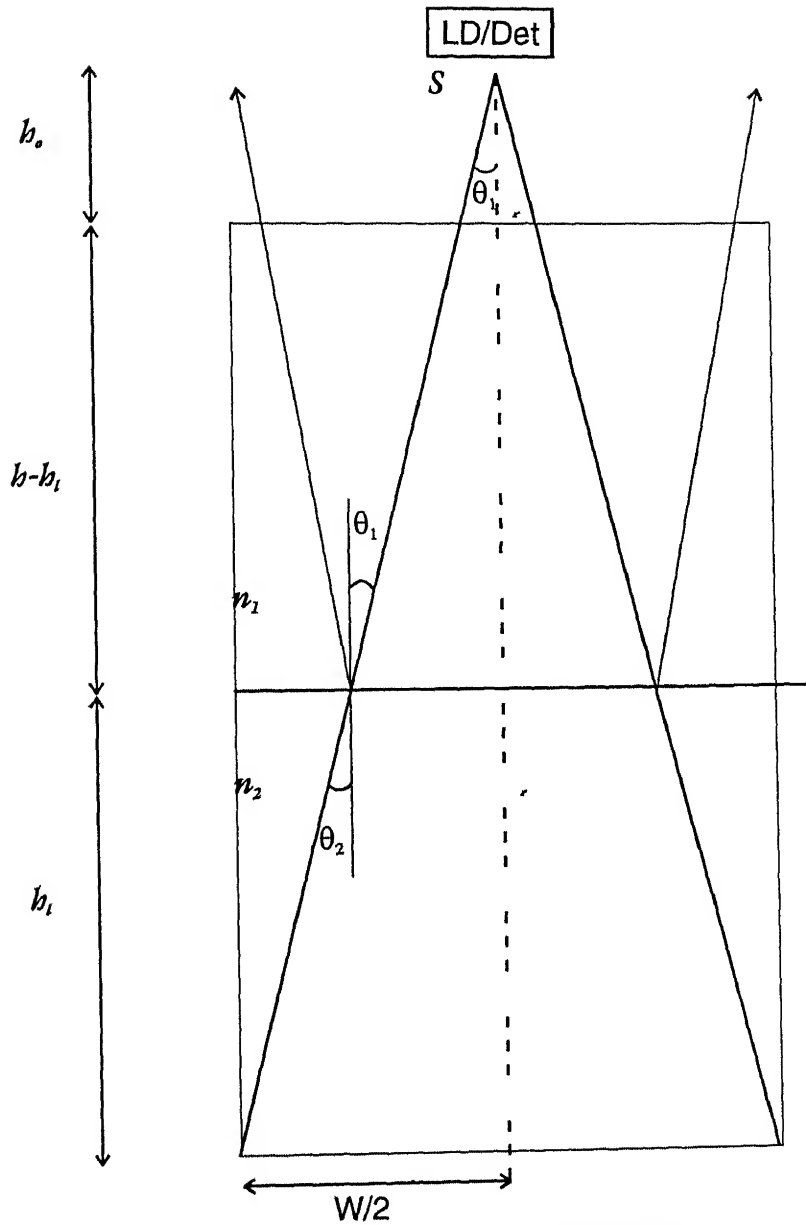**LEGEND**
LD is laser diode
Det is Detector
w is base width
θ is Half beam divergence angle

FIG. 4.3 ANALYSIS OF CONFIGURATION NO.3
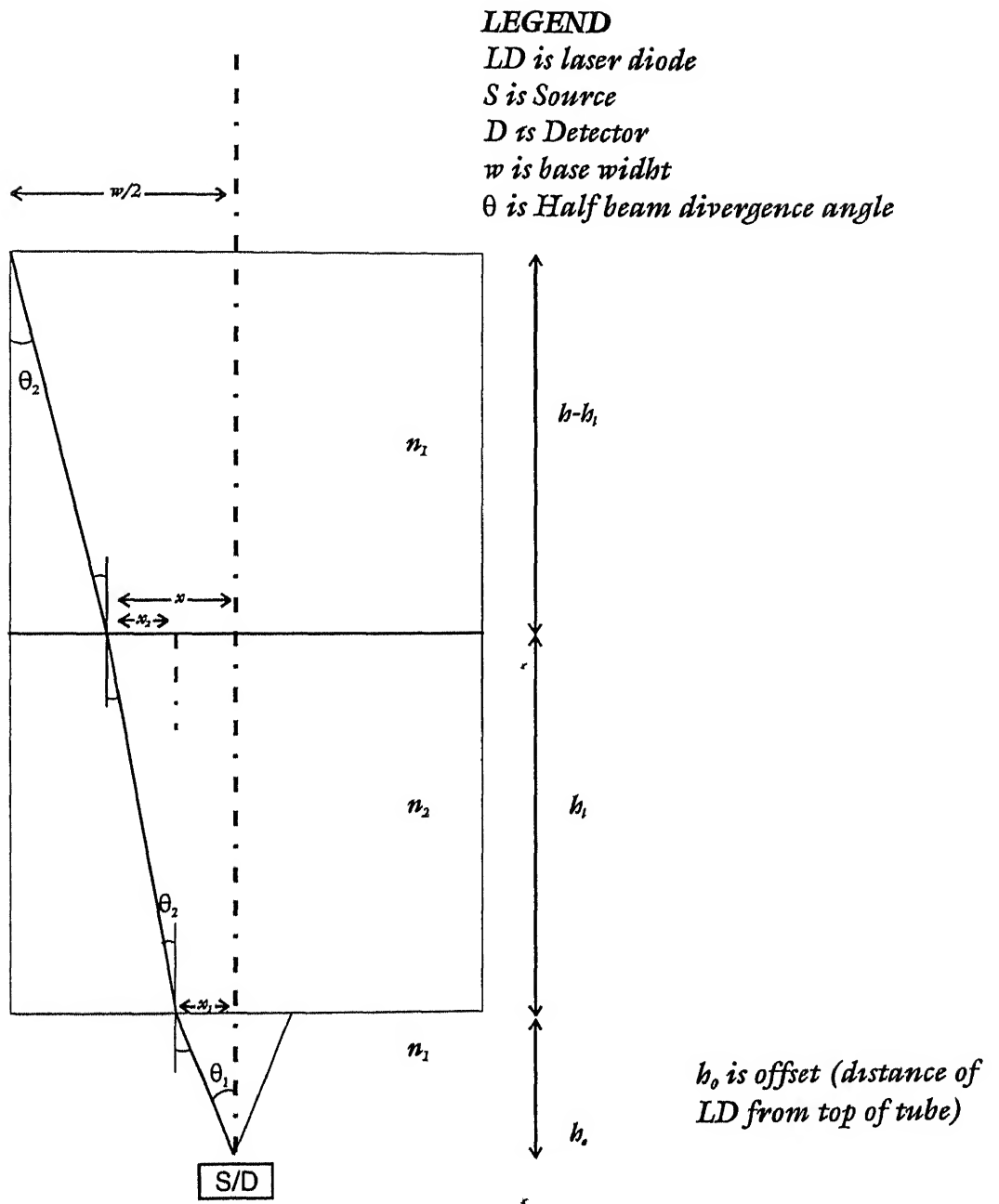(Both LD and detector placed on top of the tube)

CHAPTER 5

WAVE PROPAGATION ANALYSIS

To get more insight about the package design of our optical level sensor, the four possible architectures for the level sensor proposed in chapter 3 have been analyzed using the physical optics considerations While carrying out the analysis, the radius of curvature ' R' of the liquid surface has also been incorporated

The four possible architectures for an optic liquid level sensor were analyzed and the expression for the final spot size reaching the detector, in all the four cases was derived and the power received at the detector was calculated It was intended to select one out of these four configurations to fabricate a liquid level sensor and the parameters were chosen accordingly as explained in chapter 4

5 1 Shape of Liquid Meniscus

The shape of the liquid meniscus in any tube is curved owing to surface tension [1] The meniscus is concave or convex upwards as the liquid wets the solid container or does not wet the solid container and the value of angle of contact is acute or obtuse respectively [1] The value of θ for mercury with glass is 140° and that of water with glass is 8°

As shown in Fig (5 1), the meniscus is assumed to be hemispherical in shape and the radius of curvature 'R' of the liquid surface is accordingly evaluated using the expression for the height 's' to which a liquid rises on meeting a solid In general, when a free liquid meeting a plane vertical rigid wall, then in the two dimensional field, the height ' s ' to which the liquid climbs the rigid wall is given by the expression as under [2].

$$s^2 = 2F_t (1 - \sin \theta)/p g \qquad (5 1)$$

where θ is the angle of contact between the liquid and the solid (tube), p is the density of the liquid in kg /m^3, g is the force of gravitational acceleration and is 9 8 kg/m^2, F_t is the surface tension of the liquid

Using the expression for 's ' as explained above, the radius of curvature 'R ' can be expressed in terms of the tube radius r and height s as under

$$R = (r^2 + s^2) / 2s \qquad (52)$$

Thus equation 5 1 & 5 2 are used to determine the radius of curvature of the top of the liquid surface

Having obtained an expression for the radius of curvature of the liquid surface, in terms of other known parameters, now we will briefly consider the wave propagation of a gaussian beam in the next section.

5.2 Gaussian Beam Propagation

The normalized scalar electric field phasor (i e $U(x,y,z)$)of a circularly symmetric gaussian beam at a distance ' z ' from the output end of the source is given by [3] the expression

$$U(x,y,z) = (2/\pi) \exp((-jkz + j \Psi(z))/w(z)) \times$$

$$\exp(-(x^2 + y^2)/w(z)^2 - jk(x^2 + y^2)/2R(z)) \qquad (53)$$

where k is propagation constant $= 2\pi/\lambda$ $\Psi(z)$ is given by the expression

$$\Psi(z) = \tan^{-1}(z \lambda / \pi w(z)^2) \qquad (54)$$

and R(z) = the radius of curvature of the beam at a distance z The spot size of the beam at a distance z is given by

$$w(z) = w_o \sqrt{1 + (z\lambda/n_1 \pi w_o)^2} \qquad (55)$$

where w_o is the minimum spot size of the beam at z = 0 as has been shown in Fig (5 2), n_1 is the refractive index of the medium , and λ is the wavelength at which the laser diode is operating

From R(z) we can define a complex radius of curvature q(z) as [3]

$$1/q(z) \equiv 1/R(z) - j \lambda / \pi w(z)^2 \qquad (56)$$

The above expression for a gaussian beam is significant because the light beam coming out from the laser diode can be treated to be a gaussian beam

5.3 Power Coupled to Photodiode from a Gaussian Beam in free space

The intensity of a circularly symmetric Gaussian beam at a distance z from the output end of the source is given by [4]

$$I(r,z) = (2P_s / \pi w(z)^2) \exp(-2r^2 / w(z)^2) \qquad (5.7)$$

If the beam falls on a photodiode of radius 'd' and responsivity =1 the power coupled P_d is given by

$$P_d = \int_0^{2\pi} \int_0^{d} I(r,z)\, r\, dr\, d\theta \qquad (5.8)$$

Integrating the above expression we get

$$P_d = P_s (1 - \exp(-2d^2 / w(z)^2)) \qquad (5.9)$$

In equation (5.9) we have neglected the absorption loss inside the medium and any loss due to reflection at the medium - detector interface. Thus for a fixed value of d and P_s, the power received at detector P_d is a function of w(z) only.

Multiple reflections may take place between the glass top of the photodetector & the photodetector material but as these surfaces are not optically flat, so we do not consider multiple reflections between these two planes Fresnel Reflection losses occur at the following interface

(a)the liquid and the glass bottom of the container

(b) the glass bottom of containers and the glass top of detector and

(c) the glass top of photodetector and the photodetector material

As the Fresnel losses at these three interface are very small in comparison to the Fresnel Reflection losses which take place at the interface of the air and liquid, so we will consider the losses which take place at the interface of the air and the liquid, while evaluating the Fresnel Reflection losses

Taking into consideration the absorption losses as well as the Fresnel Reflection loss at the air liquid interface the power coupled P_d, in transmissive type of sensors (configuration No 1and 2), is given by

$$P_d = T P_s \ (1 - \exp \ (-2d^2 / w_3{}^2)) \ \exp \ (-a \ h) \hspace{3cm} (5\ 10)$$

where a is the absorption coefficient per unit length inside the liquid at the operating wavelength, d is the radius of the detector ,P_s is the source power , h is the height of liquid column and T is the loss due to Fresnel Reflection and is given by

$$T = 4 \ n_1 n_2 \ / (n_1 + n_2)^2 \hspace{3cm} (5\ 11)$$

Thus for a given value of d, P_s, w_o, λ, a, n_1 and n_2 the power coupled varies with height of liquid column hl, provided that the refractive index of the liquid (n_2) remains constant

5.3.1 Power Coupled to Photodiode in an Offseted Detector

The expression for P_d as given by equation 5 9 is based on the assumption that there is no offset between the source and detector While it may be possible to achieve this condition in case of the first two configurations (i e transmissive type of sensors) , but in configuration no's 3&4 (i e reflective type of sensors) where both the source and detector are on the same side of the tube ,it may not be possible This is because even if the source and detector are kept adjacent to each other , still the center of the detector will be offset from the center of the source by a distance equal to the sum of the radius of the source and of the detector

In reality, as shown in Fig 5 3 , there is a fixed lateral offset (q_1) between the centre of the source and detector The least value of this offset is equal to the sum of the radii of the source and the detector assuming both are placed adjacent to each other Mathematically $q_1 = d_1 + d_2$ where d_1 & d_2 is the radius of the source and detector respectively There can be lateral offset due to

(a). Angular Misalignments These are due to angular displacements namely

(i) A tilt in the liquid surface due to a tilt in the tube in which it is kept will result in a tilt in the level of the liquid surfaceand the light beam will undergo a transverse shift $'q_2'$ due to reflection

(ii) A fixed tilt offset caused by the misalignment of the light source and the photodiode during the fabrication of the sensor package (here after referred to as angular offset)

(b). Linear Misalignment Effect. There may also be a fixed lateral offset $'q_1'$ between the source and detector during the fabrication

The effect of all these three misalignments is that the optical beam is shifted in a transverse direction away from the centre of the photodiode Without loss of generality we will consider the effects of these offsets in the x -z plane only In this thesis, we will concern ourselves only with the effect of the fixed lateral offset (q_1), which will hereafter be referred to as 'q'

Now the power coupled to a photodiode is as given by equation 5 8 & equation 5 9 with the change that $r^2 = ((x-q)^2 + y^2)$ where q is the offset

thus $P_d = (2 P_s / (\pi w(z)^2)) \int_{0}^{2\pi d}\int_{0} \exp (-2((x-q)^2 + y^2)/w(z)^2) \, dx \, dy$

which reduces to

$P_d = (2P_s / (\pi w(z)^2)) \exp(-2q^2/w(z)^2) \int_{0}^{2\pi d}\int_{0} \exp(-2 r^2/w(z)^2) \exp(2 r q\cos\theta/w(z)^2) \, r \, dr \, d\theta$

(5 12)

On trying to evaluate this integral we get terms containing error function and the integral does not give a closed form expression The above expression is integrated using NAG routine [4] (DOIDAF) based on the

method described by Patterson [5], [6] A programme was written in fortran language to evaluate the value of this integral and hence power coupled to the photodetector for different values of liquid level The programme can be run by any user to generate data files by inputting various values of design parameters such as tube height h , tube width w , detector radius d_2 ,refractive index of liquid n_2 and the value of the offset 'q'

Taking into consideration the absorption losses as well as the Fresnel Reflection loss at the air liquid interface the power coupled to the detector is given by

(a) **For configuration No 3** (both source & detector at top of tube)

$$P_{det} = R\, P_d \qquad\qquad\qquad (5\ 13)$$

where $R = (1 - T)$

(b) **For configuration No 4** (both source & detector at bottom of tube)

$$P_{det} = R\, P_d\ \exp\ (-2a\,h) \qquad\qquad\qquad (5\ 14)$$

where a is the absorption coefficient per unit length inside the liquid at the operating wavelength ,d is the radius of the detector , h is the height of liquid column, T is the loss due to Fresnel Reflection and P_d is as given by equation 5 12   The coupling efficiency is defined as

$\eta = (P_d / P_s)100$, where (P_d is as given by equation (5 10) for configuration no 1 & 2

$\eta = (P_{det} / P_s)100$, where (P_{det} is as given by equation (5 13) and (5 14) for configuration no 3 &4

5 4 First Configuration : Expression for Spot Size & Power   for Sensor Configuration No 1

As shown in Fig (5 8) , if some liquid of refractive index n_2 partially fills up the gap of length z between the optical source and photodiode , then the optical beam will propagate partially through air (distance z - h) and partly through a liquid column of height h The light travelling from the bottom of the

tube thus encounters a concave dielectric interface whose ray matrix in terms of A,B,C,D parameters [7] is given by

$$\begin{bmatrix} 1 & 0 \\ \dfrac{(n_2 - n_1)}{n_2\,R} & \dfrac{n_1}{n_2} \end{bmatrix}$$

(5 15)

The detailed derivation of the above expression has been done in appendix B In the above expression, R is the radius of curvature of the liquid and n_1 & n_2 are the refractive indices of air and liquid respectively

The complex beam parameters at various planes are as under [5]

q_1 - at plane 11' i e at the output of the laser diode

q_2 (-) - at plane 22' i e above the air liquid interface (as viewed from the top of the tube)

q_2 (+) - at plane 22' i e below the air liquid interface (as viewed from the top of the tube)

q_3 - at plane 33' i e at the input end of the detector

At plane 11' that is at source (z =0) , the complex beam parameter q_1 is given by [6]

$$1/q_1 = - \, \jmath\, \lambda \, / \, n_1\, \pi\, w(z)^2$$

(5 16)

.

where w_o is the size of gaussian beam measured at z =0 The transformed beam parameter q_2 (-) just to the left of the air liquid interface is given by q_2 (-) = q_1 + (z - h) The beam parameter q_2 (+) , just below the air liquid interface is given by

$$q_2\,(+) = \left[\dfrac{A q_2(-) + C}{B q_2(-) + D} \right]$$

(5 17)

where A, B,C, D are the elements of the ray matrix given by expression (5 15) Finally the beam parameter q_3 at the liquid detector interface is given by

Finally the beam parameter q_3 at the liquid detector interface is given by $q_3 = (q_2 (+) + h)$ Also, q_3 is related to the beam spot size w_3 and radius of curvature of the beam R_3, through the equation

$$1/q_3 = 1/R_3 \quad - \quad j \lambda / n_2 \pi w_3{}^2 \qquad\qquad (518)$$

From equations (5 16), (5 17) and (5 18), the expression for beam spot size at plane 33' is derived at appendix 'A 'and is given by

$$w_3 = w_o \sqrt{(1 + (n_2 - n_1)h / n_2 R)^2 + (g\lambda / n_1 \pi w_o{}^2)^2} \qquad\qquad (519)$$

where $g = ((n_2/n_1) h / n_2 R + 1)(z - h) + (n_1/n_2)h$

If the liquid is kept in a tube with a large diameter ,the surface of the liquid is normally flat in shape For a flat surface with no radius of curvature and the expression for beam spot size at plane 33' is given by

$$w_3 = w_o \sqrt{1 + (g\lambda / n_2 \pi w_o{}^2)^2} \qquad\qquad (520)$$

where $g = h + (n_2/n_1)(z - h)$

5.5 Expression for Spot Size & Power received for Sensor Configuration No 2

In this configuration the detector is at the top of the tube and the source is at the bottom as shown in Figure (5 10). A liquid of refractive index n_2 partially fills up the gap of length z between the laser diode & the photodetector and the optical beam propagates a distance ' h ' through the liquid and the remaining distance (z-h) through the air The light travelling from the bottom of the tube thus encounters a covex dielectric interface whose ray matrix in terms of A,B,C, D parameters [7]is given by

$$\begin{bmatrix} 1 & 0 \\ \dfrac{(n_2 - n_1)}{n_1 R} & \dfrac{n_2}{n_1} \end{bmatrix} \qquad\qquad (5\ 21)$$

Proceeding in the way we analyzed configuration no 1 in the previous section we can show that the expression for the spot size at the detector is given by

$$w_3 = w_o \sqrt{(1 + (n_2 - n_1)(z - h)/n_1 R)^2 + (g\lambda/n_2\pi w_o^2)^2} \qquad\qquad (5\ 22)$$

where $g = ((n_2 - n_1)h/n_1 R + n_2/n_1)(z - h) + h \qquad\qquad (5\ 23)$

5.5.1 Total Internal Reflection Considerations

As in sensor configuration no 2 , the light is travelling from a denser to a rarer medium and there is a possibility of total internal reflection and hence the cone of light actually passing through from denser to rarer medium may vary. We analyzed to discern weather there is any appreciable change in the spot size and the illumination cone , on going from denser to rarer medium , and the same is explained in the subsequent paragraph

As shown in Fig (5 5) , a gaussian beam of light incident on a flat interface between two mediums is shown . Let θ be the angle of the illumination beam incident on the liquid surface and θ' is the angle of the ' fraction ' of illumination beam which passes through to the rarer medium The critical angle $\theta_c = \sin^{-1}(n_1/n_2)$ Thus when $\theta' > \theta_c$, total internal reflection occurs Thus $\theta' \leq \theta_c$, while considering the fraction of beam of light passing through the interface Now for planer angles θ & θ' , $\tan\theta = r/R(z)$ and $\tan\theta' = r'/R(z)$ But for large distances $R(z)$, we can approximate the length of the arc subtended to be .

$r = R(z)\ \theta$ and $r' = R(z)\ \theta'$ $\qquad\qquad (5\ 24)$

Also $\theta' \leq \theta_c$ and $\theta = \theta_{beam}$, where θ_{beam} is the far field beam angle [3] given by

$$\theta_{beam} = \lambda / \pi w_o \qquad\qquad (5\ 25)$$

Using equations (5 24) & (5 25) we can show that for large z, the spot size w(z) is given by

$$w(z) \approx z\lambda / \pi w_o{}^2 n$$

Also for large distances z,

$$r = (x^2 + y^2)^{\frac{1}{2}} = z\lambda / \pi w_o\, n \quad \text{Thus for far field } z \geq \pi w_o{}^2 n \,,\ r \approx w(z)$$

From equation 5 24 & 5 25 we can show that $r' = r\, \theta_c / \theta_b$ But as $r \approx w(z)$, thus

$$w(z)' = w(z)\, \theta_c / \theta_b \qquad\qquad (5\ 26)$$

where w(z) is the actual spot size of the beam at a distance z in any single medium and w(z)' is the actual spot size at a distance z if the beam travels from a denser to a rarer medium Substituting for w(z) and θ_c we get

$$w(z)' = \theta_c (\pi w_o\, n) / \lambda \ \ w_o \sqrt{1 + (z\lambda / n_1\, \pi w_o)^2} \qquad\qquad (5\ 27)$$

Numerically substituting the values of various constants and variables in the expression for far field distance 'z' and for θ_b we obtain certain results which are tabulated at table 5 1 & table 5 2 respectively and the inferences drawn from them are stated in the subsequent paragraphs

From equation (5 27) we had the relation $w(z)' = w(z)\, \theta_c / \theta_b$, which means that w(z)' will be a fraction of or a percentage of w(z) only in the case when θ_b is $> \theta_c$ In all other cases, so long as $\theta_c > \theta_b$, the complete beam will pass through the interface, into the rarer medium

From the results tabulated we find that θ_b is very small compared to θ_c and for the range of values over which the optical sensor would be designed to function, it is seen that θ_b is at best $= 8\ 63^o$ and corresponding to that, the far field is $6\ 6\ \mu m$, that is a very small distance compared to the tube length

Thus we may assume that most of the gaussian beam of light would pass through from the liquid to air in configuration no 2 and undergoes refraction governed by the ray matrices for the spherical dielectric interface The final spot size in sensor configuration no 2 will be as given by equation (5 22)

The power coupled to the photodiode is as given by the equation (5 10)which is reproduced below

$$P_d = T P_s\ (\ 1\text{-}\exp\ (\text{-}2d^2 / w_3{}^2\ )\ )\ \exp\ (\text{-}a\,h\ )$$

where a is the absorption coefficient per unit length inside the liquid at the operating wavelength, h is the height of liquid column, T is the loss due to Fresnel Reflection, d is the radius of the detector & P_s is the source power Fresnel Reflection losses occur at the interface between (a)the glass bottom of container and the top of laser diode ,(b)the air and the glass top of the photodetector, and (c) the glass top of photodetector and the photodetector material but these are very small in comparison to the Fresnel Reflection losses which take place at the interface of the air and liquid & air .

5.6 Expression for Spot Size and Power received for Sensor Configuration No 3

In this sensor configuration both the source and detector are at the top of the tube as shown in Figure (5 12) .The light travelling from the top of the tube thus encounters a liquid surface which acts like a concave reflecting surface of radius of curvature R whose ray matrix in terms of A, B, C, D parameters [7]is given by

$$\begin{bmatrix} 1 & 0 \\ \dfrac{-2}{R} & 1 \end{bmatrix} \qquad\qquad (5\ 28\ )$$

provided R >0 Proceeding in the way we analyzed configuration no 1 in the previous section we can show that the expression for the spot size at the detector is given by

$$w_3 = w_o \sqrt{(1 - 2(z-h)/R)^2 + (2(z-h)\lambda / n_1 \pi w_o^2)^2 (1-(z-h)/R)^2} \qquad (5\ 33)$$

where h is the height of liquid column from the bottom of the tube .The power coupled to the photodiode is as given by the equation 5 13 explained earlier

5.7 Expression for Spot Size and Power received for Sensor Configuration No 4

In this sensor configuration both the source and detector are at the bottom of the tube as shown in Figure (5 13) . The light travelling up from the bottom of the tube encounters a liquid surface which acts like a convex reflecting surface of radius of curvature R , and gets reflected from it The ray matrix of the convex reflecting surface in terms of A,B,C, D parameters [7]is given by

$$\begin{bmatrix} 1 & 0 \\ \dfrac{2}{R} & 1 \end{bmatrix} \qquad (5\ 35)$$

provided R >0   Proceeding in the way we analyzed configuration no 1 in the previous section we can show that the expression for the spot size at the detector is given by

$$w_3 = w_o \sqrt{(1 + h/R)^2 + (2h\lambda / n2\pi w_o^2)^2 (1+2h)/R)^2} \qquad (5\ 39)$$

where h is the height of liquid column

5.8 Summary

In this chapter we have analyzed the four configurations of a low cost optical sensor using physical optics considerations We have derived expressions for the spot size available at the detector and the power received by the detector in all the four cases and programmes have been written to evaluate the power coupled to the photodetector and hence its coupling efficiency ,for different values of liquid

level   We have also analyzed the total internal reflection considerations in case of configuration no 2 In the next chapter we will input numerical values for the various design parameters in the programmes and generate data files to plot the variation in the coupling efficiency with respect to the liquid level is plotted in each of the four configurations

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TABLE 5 1

Variation in far field $z \geq (\pi w_0^2 n / \lambda)$ for various values of w_o and λ

Far Field $z \geq (\pi w_o^2 n / \lambda)$

$\lambda \downarrow w_o \rightarrow$	$1\,\mu m$	$5\,\mu m$	$10\,\mu m$	$20\,\mu m$	$40\,\mu m$
$0\,4\,\mu m$	$10\,\mu m$	$261\,\mu m$	umm	4 17 mm	16 71 mm
$0\,63\,\mu m$	$6\,6\,\mu m$	$165\,8\,\mu m$	0 66 mm	2 65 mm	10 61 mm
$0\,7\,\mu m$	$5\,96\,\mu m$	$149\,\mu m$	0 596 mm	2 38 mm	9 55 mm

TABLE 5.2

Variation in half beam angle θ_b for various values of w_o and λ

$$\theta_b{}^\circ = \theta_b \text{ (in radian) } (180/\pi) \text{ where } \theta_b(\text{rad}) = \lambda / w_o\, n\pi$$

$\lambda \downarrow w_o \rightarrow$	$1\,\mu m$	$5\,\mu m$	$10\,\mu m$	$20\,\mu m$	$40\,\mu m$
$0\,4\,\mu m$	$5\,48^\circ$	$1\,09^\circ$	0.0548°	$0\,27^\circ$	$0\,14^\circ$
$0\,63\,\mu m$	$8\,63^\circ$	$1\,72^\circ$	$0\,86^\circ$	$0\,43^\circ$	$0\,22^\circ$
$0\,7\,\mu m$	$9\,59^\circ$	$1\,91^\circ$	$0\,96^\circ$	$0\,48^\circ$	$0\,24^\circ$
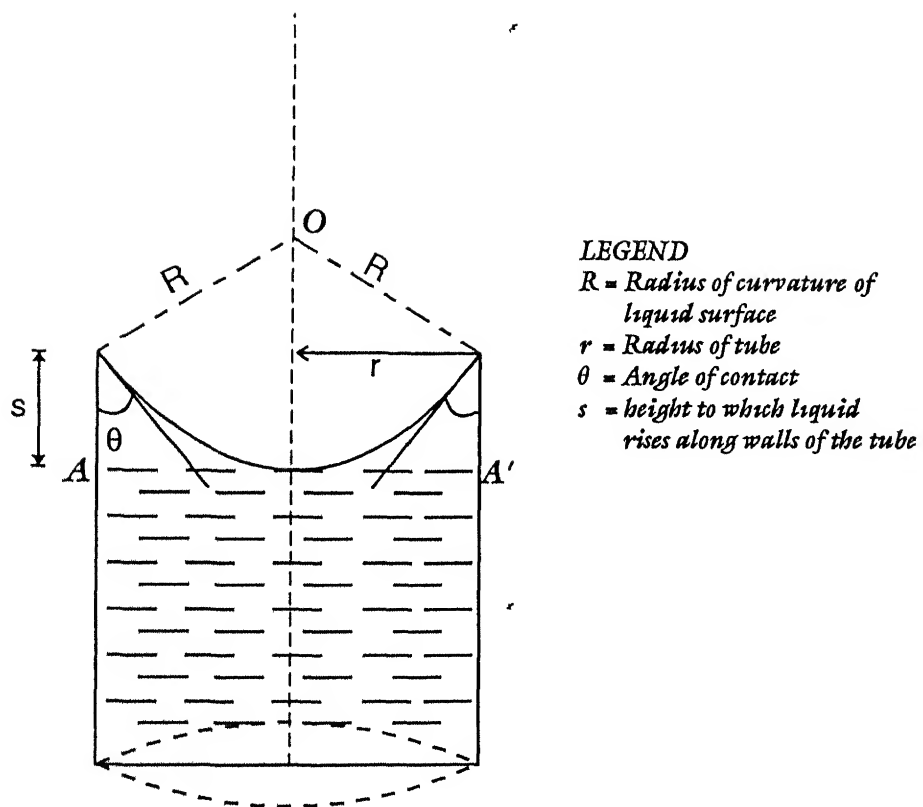
Fig. 5.1 *Radius of Curvature of liquid surface*

LEGEND
R = *Radius of curvature of liquid surface*
r = *Radius of tube*
θ = *Angle of contact*
s = *height to which liquid rises along walls of the tube*
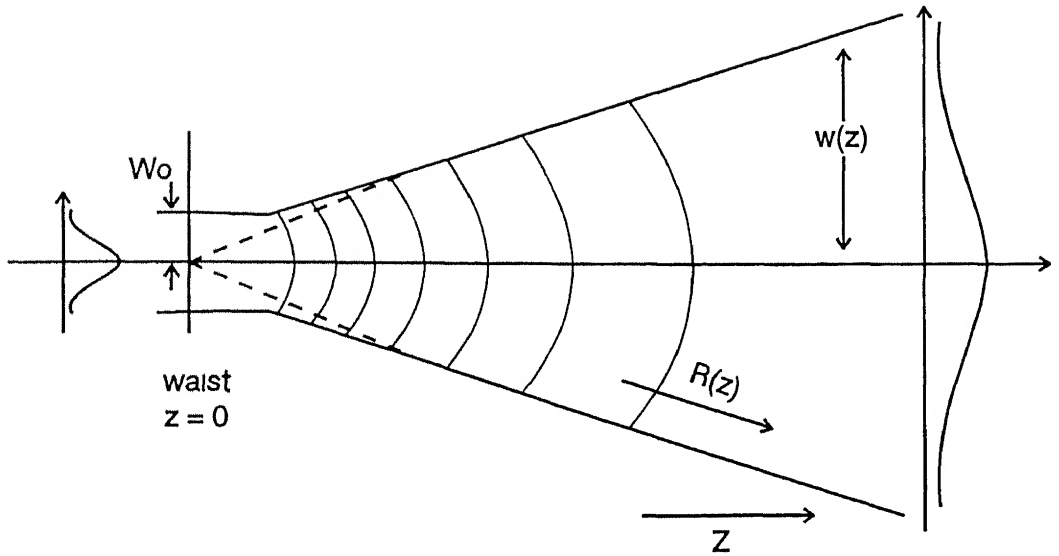
Fig. 5.2 Notation for a lowest order gaussian beam diverging away from its waist
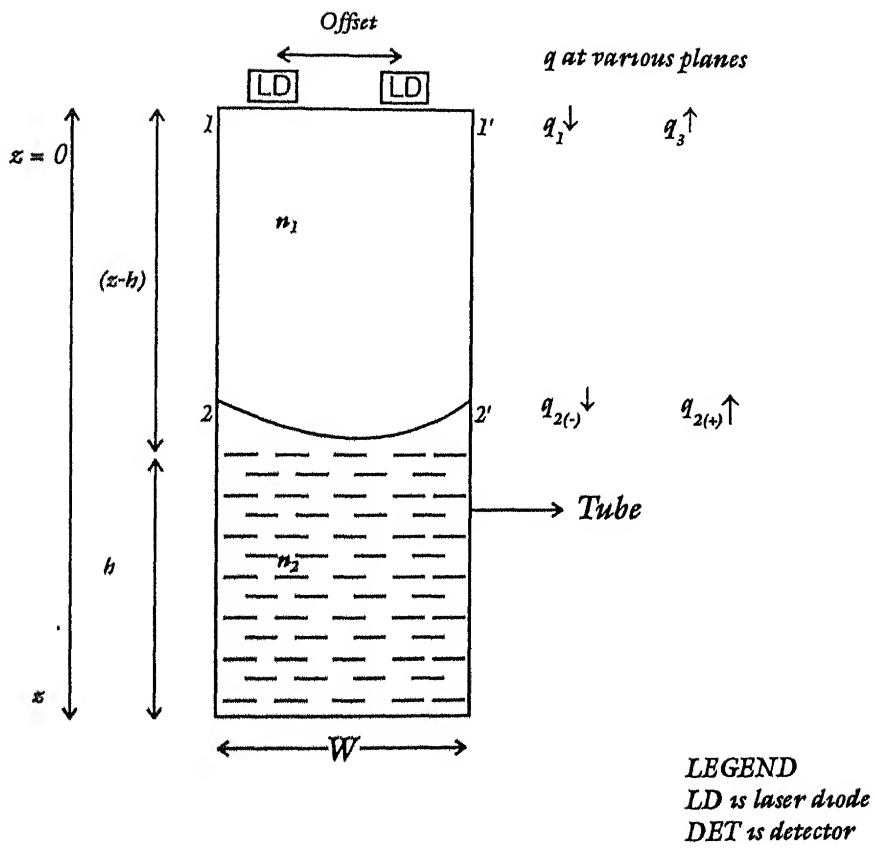
Fig. 5.3 The detector at an offset from the source

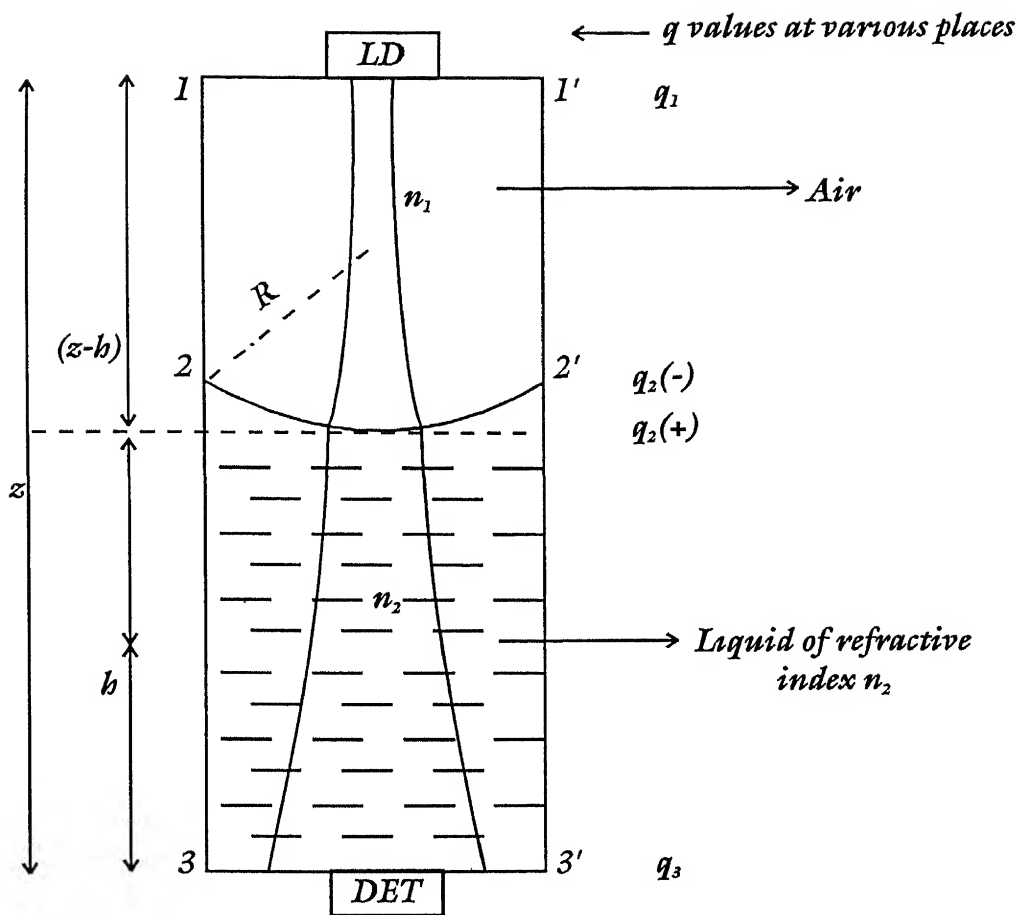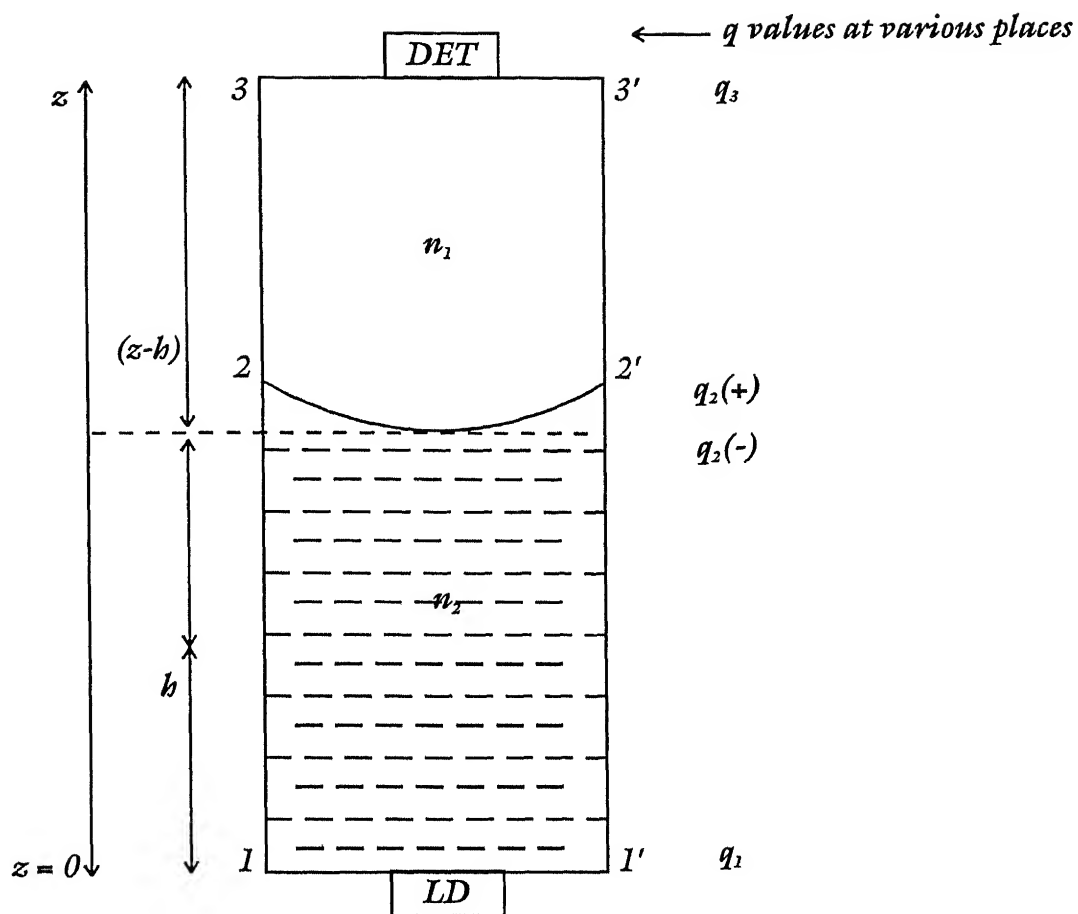Fig. 5.4 *Spot size analysis for configuration No. 1*

z

$z = 0$

3 DET $3'$ q_3

n_1

$(z-h)$ 2 $2'$ $q_2(+)$

$q_2(-)$

n_2

h

1 LD $1'$ q_1

← *q values at various places*

Fig. 5.5 Configuration No. 2

θ *is half beam divergence angle at which light is incident*

LIQUID

AIR

R (z)

θ

θ`

r

r'
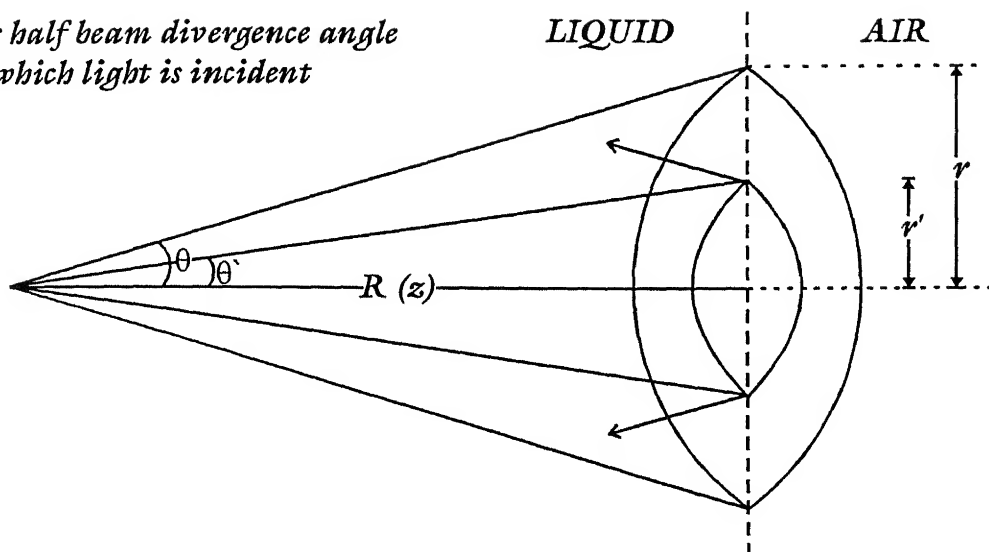
Fig. 5.   Total internal reflection condition analysis for configuration No. 2

Offset

z = 0

(z-h)

z

h

LD ⟷ LD

1   1'

n_1

2   2'

n_2

W

q at various planes

$q_1\downarrow$ $q_3\uparrow$

$q_{2(-)}\downarrow$ $q_{2(+)}\uparrow$

LEGEND
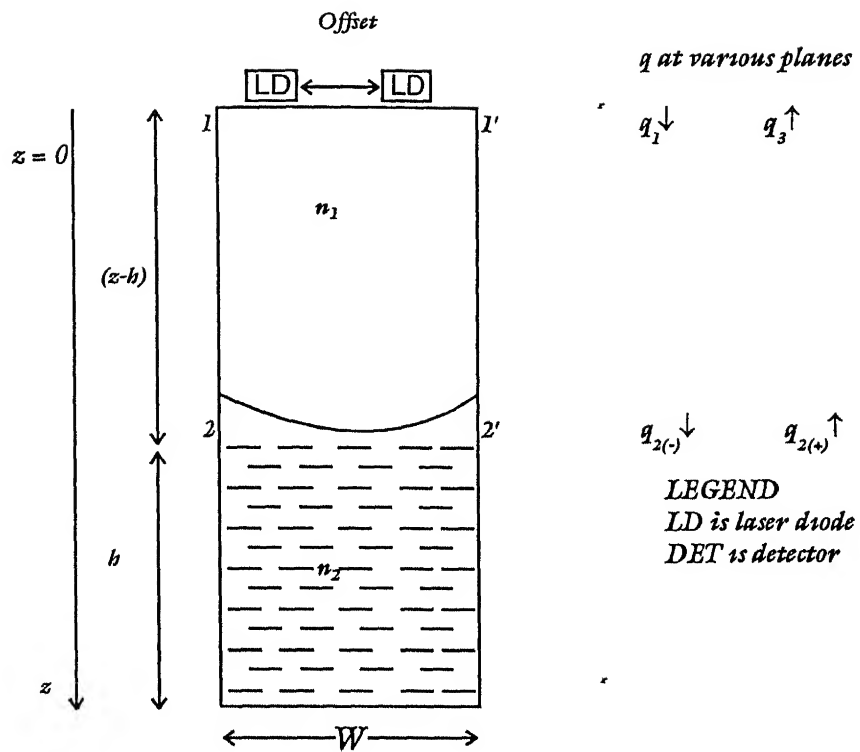*LD is laser diode*
DET is detector

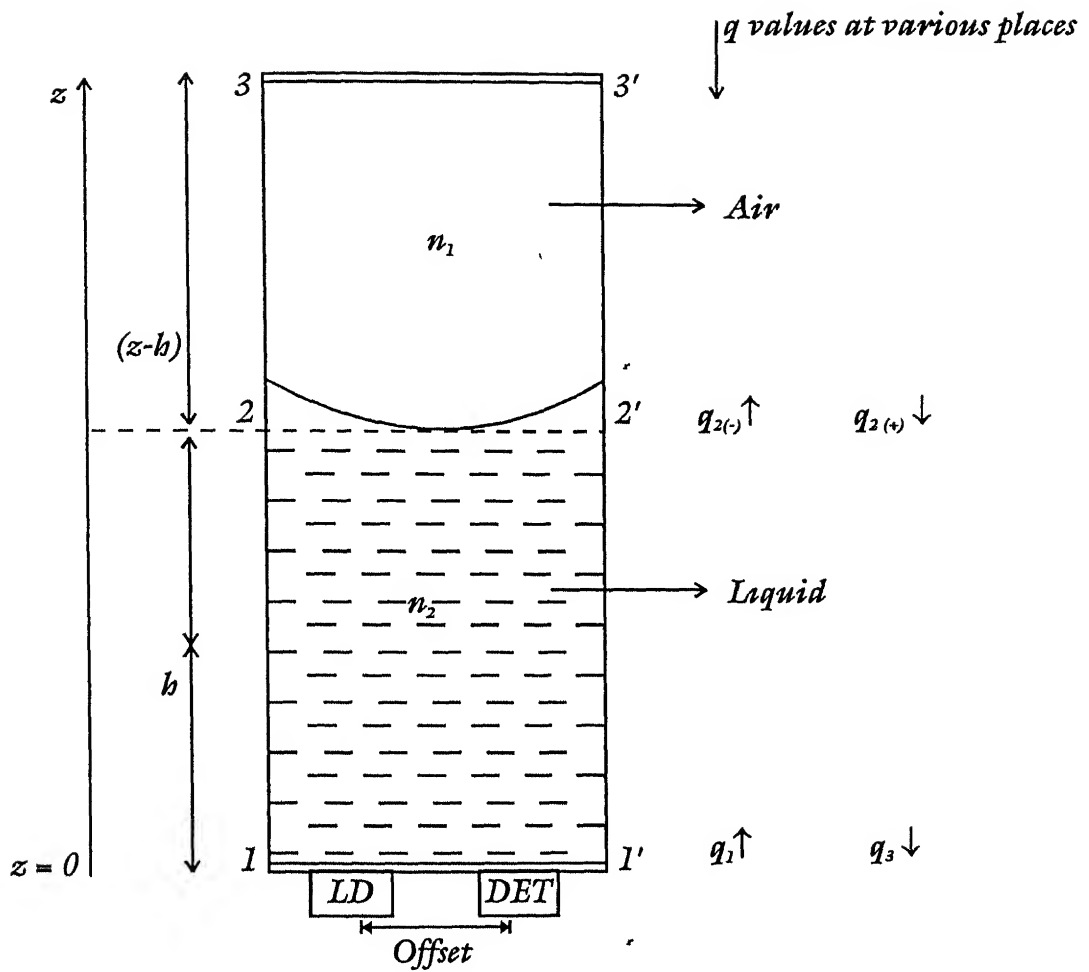*Fig. 5.7 Sensor configuration No. 3*

Fig. 5.8 Sensor configuration No. 4

CHAPTER 6

SIMULATION RESULTS

In the previous chapter we derived expressions for the spot size available at the detector and the power received by the detector in all the four configurations of an optical sensor Programmes to evaluate the power coupled to the photodetector and hence it's coupling efficiency, for different values of liquid level have also been written. In this chapter we will select various design parameters and input their values in the programmes to generate data files These data files will be used to plot the variation in the coupling efficiency with respect to the liquid level in each of the four configurations Finally, we carry out a comparative analysis of the results obtained from the simulation of all the four configurations, with an aim to select a feasible model from amongst them.

6.1 Analysis of the Results

6.1.1 Test Data Used Various design parameters which have to be selected are as follows

    (a) Diameter of tube

    (b) Height of tube

    (c) Refractive index of liquid

    (d) Radius of detector

    (e) Radius of source

    (f) Wavelength of laser diode

    (g) Waist spot size at give wavelength

(h) Output power of source

(j) Absorption coeff /mm at given wavelength

(k) Surface tension of liquid

(l) Angle of contact of liquid with solid

(m) Density of liquid

There is a requirement for an optical window to be put on the base of the tube for transmissive type of sensors (sensor configuration No's 1 and 2) Optical windows come in specified sizes and due to the complexity in their fabrication process, their cost increases as their size becomes larger For our low cost optical sensor, the optical window should be large enough to accommodate the source and detector Thus an optical window with a diameter of approximately an inch (25 4 mm) would suffice for our purpose Keeping a margin of 1 2 mm on either side of the diameter to allow for fixing the optical window to the walls of the tube, at the base of the tube we are left with an optical window with a diameter of 23 mm.

The tube in which the liquid is kept though should not be so long that it becomes unwieldy to handle yet it should be long enough to allow proper measurement of the liquid level by our optical sensor In view of this, a tube of length = 10 cm (100 mm) would meet the requirement Moreover, the range over which the sensor should be able to function should be starting from 5 mm from the base of the tube to 10 mm short of the top of tube In view of this, a tube of length = 11 5 cm (115 mm) would meet the requirement as this would allow measurement to be done over a range of 10 cm (100 mm) Moreover, Hindustan Aeronautics Limited (Lukhnow) had also projected the requirement that the liquid measurement should be possible over a length of 10 cm [4]

The liquid selected for the purpose of our analysis is water and the refractive index, absorption coefficient, density and the angle of contact has been accordingly selected as 1 33, 7 6 10^{-3}, 1000 kg/m^3 and 8° respectively.

Looking through the data sheets of various low cost laser diodes in the visible region (at a wavelength of say 670 nm), the radius was about 1 to 2 mm The power output of such laser diode can be in the range of 1- 2 mW, which is adequate for the requirement of our optical sensor The minimum spot size of the gaussian beam at the operating wavelength is 100 microns These lasers are available with simple optics to convert the beam to a circular spot The list of design parameters thus selected is tabulated at table 6 1

6.1.2 Variation in Power and Coupling Efficiency

The graphical plots of the variation in the coupling efficiency for sensor configurations no's 1,2 and 3 are shown in Fig's 6 1, 6 2 and 6 3 respectively Sensor configuration no 4. in which both the laser diode and the detector are at the bottom of the tube has been discarded at the outset as its coupling efficiency was between 0 24% to 0 34%, which is very small in comparison to the coupling efficiency achieved in the other 3 configurations The reason for this rather low coupling efficiency is because in configuration no 4, the absorption inside the liquid is double the loss in case 1and2

It is seen from the plots in Figs 6 1 and 6 2 that in case of the configuration no's 1and 2, the power decreases continuously as the liquid level (h_1) is increased This is because the detector, being aligned with the source and placed in the centre of the tube will always fall within the cone of light being sent by the Laser Diode With an increase in h_1, the cone of light is spread over a larger area thus the intensity of light being received at detector decreases Also , the absorption loss increases with h_1

The variation of power coupling efficiency (Eff) in the graph is lenlar throughout But in the region between $h_1 = 10$ mm to $h_1 = 85$ mm, the power coupling efficiency is reasonably in both these configurations Thus both these configurations can be used for measuring level in this region. With the radius of detector chosen as 2 mm the range of variation in coupling efficiency, is from 14 % to 77 %, for sensor Configuration no 1 and from 42% to 61% for Configuration no 2 However, when the radius of the

detector is increased to 4 mm, the range of variation in coupling efficiency, for Configuration no's 1 and 2 is from 43 % to 96% and from 42% to 93% respectively

The variation in coupling efficiency vs liquid level for configuration no 3, was plotted keeping the radius of detector and source at 2 mm and 1mm respectively The offset is kept at the minimum value of 3 mm (i e $q = d_1 + d_2$) On analysis of Fig 6 3, it is found that the response can be divided into two regions - the front slope and the back slope The front slope of the plots pertains to the region of partial overlap between the detector and the cone of light reflected from the liquid surface and the back slope of the plot pertains to the region of complete overlap

The coupling efficiency increases with h_1 in the region of front slope This is due to the fact that initially, as the liquid level increases, the intensity of light coupled to the detector increases thus the power coupled to detector (P_d) and the power coupling efficiency (Eff) increase After a certain liquid level, the light reflected from the liquid surface falls on the complete area of the detector and maximum P_d and Eff are achieved After this stage, though there is no further increase in the area of the detector which receives light, yet the intensity of light falling per unit area decreases and thus P_d and Eff decrease and this is the region of back slope of the plot

6.2 Selection of a Feasible Design for an Optical Sensor

On comparing the results obtained and considering the practical problems associated with the proposed design, we come to the under mentioned conclusions

(a). **Sensor configuration no 4** (both source and detector at the bottom), can be discarded as it involves maximum absorption losses because the liquid travels up and down inside the liquid column

(b). **Sensor configuration no's 1 and 2**, though provide 40% to 97% coupling efficiency, yet suffer from the following drawbacks

(i) In the presence of suspended particles in the liquid, the absorption per unit distance inside the liquid will vary because the presence of suspended particles makes the liquid non-homogeneous in nature

(ii) These types of sensors are prone to misalignment errors and alignment considerations are very critical in these sensors

(iii) From the packaging aspect, it is preferable to place both the source and detector together in a compact housing But in configuration no 1 and 2 the source and detector are at opposite ends of the device containing the liquid

(iv) It is practically difficult to place any component (laser diode or detector) at the bottom of the tube

(c). In sensor configuration no 3 (both source and detector on top of the tube), the power received at the detector is less as compared to that in configuration no 1 and 2 and the coupling efficiency in the region of back slope, varies from 1% to 14% Despite this obvious disadvantage, this type of sensor has certain advantages, which are as under

(i) For a given liquid kept in a container of a specified solid material, the shape of the liquid meniscus will not vary over a period of time and thus the pattern of the light being reflected from its surface will not vary with time

(ii) Impurities that contaminate the liquid are of two types - suspended impurities and impurities that float The floating variety can be separated from the liquid easily by various mechanical means Even if suspended impurities are there in the liquid, then due to gravity they are likely to settle down and would not float on the surface Thus the reflection from the surface is uniform and there is no variation in power received at the detector, for a particular liquid, because of impurities in the liquid.

(ii) As both source and detector are on top of the tube, so it is easier from the aspect of packaging and manufacturing because the electronic circuitry associated with laser diode and detector can be placed together at one place

(iv) Electronically we can detect signals in the range of nano amps The photocurrent from the detector in this configuration is in the range of micro amps to nano amps and is sufficient to be detected by the electronic circuitry

In view of the above, sensor configuration no 3 was selected as a feasible design for a low cost optical sensor In the next section we will discuss the various types of misalignments that can take place in an optical liquid level sensor

6.3 Effects of Variation in Various Parameters

To appreciate the effect of the the various design parameters on the coupling efficiency, keeping all other design parameters the same , one particular parameter was varied and its effect was analysed The effect variation of various parameters has been considered and the analysis of the same is given in the subsequent paragraphs

In Fig 6 4, coupling efficiency with respect to liquid level h_1 has been plotted for values of offset varying from 3 mm,4 mm, 5 mm and 6 mm, for a given radius of the detector (d2=2 mm)

I   As the offset q is made to vary from 3 mm to 4 mm, 5 mm and 6 mm, efficiency decreases sharply with an increase in offset because as q increases, the amount of light being coupled to detector decreases This is because the cone of light reflected by the liquid surface partially covers the detector The coupling efficiency is maximum when the offset is minimum and is 3 mm (i e q= d_1 + d_2) It is also seen that as the offset is increased, the dead zone of the sensor decreases andthe effective range over which sensing is possible decreases

The radius of the detector 'd$_2$' was varied from 2 mm to 5 mm, in steps of 1 mm and a plot of Eff vs h$_1$, for each variation was taken. While taking these plots, the offset was kept to the minimum possible value corresponding to the upper limit of variation in d2 The same is shown in Fig 6 5 Similar observations were made as seen in the case of fig 6 4 Eff decreases with an increase in the offset However it is seen that these graphs that the reverse slope changes uniformly and is suitable for sensing purposes

It i salso seen that for the same offset, Eff increases as the radius of detector is increased This is because with an increase in d$_2$ the area of detector increases and thus more light intensity can be coupled to it, for the same offset Thus for an offseted detector based optical sensor, ideally the offset should be kept to the minimum, that is equal to the sum of the radius of the source and the detector, and the radius of the detector should be large

The waist spot size is varied from 0 1mm, 0 25mm, 0 5mm and to 1mm and the variation in coupling effficiency with respect to the liquid level is plotted as shown in Fig 6 6 It is seen that efficiency increases with an increase in the waist spot size as more power is being coupled to the deector It is also seen that as waist spot size increases, the range of the sensor increases and there is a smaller dead zone where our optical sensor will be unable to sense the level of the liquid.

The values of the refractive index of three fluids was selected to study the variation in coupling efficiency with respect to liquid level As shown in Fig 6 7, there is only a slight amount of variation in the coupling efficiency on varying the value of refractive index of the liquid. It is seen that efficiency decreases wih an increase in the refractive index of the liquid This is because with an increase in the value of n2, the Fresnel Coefficient decreases and thus P$_d$ and Eff decrease Also, thevariation in final spot size is dependent on the value of the refractive index of the liquid effects the final spot size which in turn effects the coupling efficiency

On varying the diameter of the tube, there is a change in the radius of curvature of the liquid surface which in turn effects the coupling efficiency From Fig 6 8 it is seen that as tube diameter is increased,which implies that as the liquid surface tends to become flat, the maximum amount of power gets

coupled to the detector at a lesser value of liquid level This is due to the dependence of the spot size on the value of 'R'

It is also seen that as the value of tube diameter (and thus R) increase, the gradient of back slope of the plot between coupling efficiency and liquid level becomes gradual and is suitable for the purpose of sensing

6.4 Annular Detector based Optical Sensor

An offseted detector based optical sensor suffers from the disadvantage that it is less efficient as compared to an optic sensor with no offset Also, the offset is prone to vary over prolonged operation and thus the sensor is required to be recalibrated periodically To do away with the need to incorporate this offset a design of an Annular detector based optic sensor has been proposed in this section

Shown in Fig 6 9 is an annular detector with an outer radius = d_2 and inner radius = d_1, with the source placed in the centre of the annular ring Now the power coupled to a photodiode is given by

$$P_d = \int_0^{2\pi} \int_{d1}^{d2} I(r,z) r \, dr \, d\theta$$

where $I(r,z) = (2 P_s / (pi \, w(z)^2)) (exp(-2 r^2 / w(z)^2))$ \hfill (6 1)

Integrating we get

$$P_d = P_s \{ exp(-2 d_1^2 / w(z)^2) - exp(-2 d_2^2 / w(z)^2) \}$$ \hfill (6 2)

Taking into account the Freznel Reflection loss, the final expression for power is

$$P_d = P_s R (exp(-2 d_1^2 / w(z)^2) - exp(-2 d_2^2 / w(z)^2))$$ \hfill (6 3)

where $T = 4 n_1 n_2 / (n_1 + n_2)^2$ and $R = (1-T)$

Four different sizes of annular detector are taken with the inner radius fixed at 1 mm and the outer radius 'd_2' varied from 2 mm to 5 mm, in steps of 1 mm. The coupling efficiency of detector (Eff) is plotted against the liquid level for a tube of length = 115 mm and plots, as shown in Fig 6 10, are seen. It is observed that as d_2 increases, coupling efficiency increases as the area of the detector increases. It is also seen that as the value of 'd_2' increases, the gradient of back slope of the plot between coupling efficiency and liquid level becomes gradual and is suitable for the purpose of sensing, though in this case the range of the sensor decreases and dead zone increases

However, the most important aspect observed is that the front slope in the case of the plots for an annular detector is more gradual and is over a longer range of h_1 as compared to that seen in Fig 6 3(a case of lateral offset q) Thus the sensor is able to operate over a greater range, if an annular detector is used in the optical sensor

6.5 Responsivity and Dead Zone of an Annular Ring Shaped Detector

As brought out from Fig 6 10, the response of an annular ring shaped detector is different from that of a detector with an offset and it has thus to be calibrated accordingly

This type of detector has a uniformly varying front slope, which can be used for sensing From Fig 6 18 and Fig 6 19 it is seen that for a specific d_2 d_1 ratio, a larger value of d_1 gives us a greater back slope over which sensing may be carried out

The variation in Eff with respect to h_1 can be detected till the 100mm mark , which is approximately 20% more than the range over which the offseted detector can sense the variation in liquid level It also meets our specifications in that it can almost sense over the complete range from 5mm to 105mm Beyond the 100mm liquid level, this detector is unable to sense and the region from 100mm to 105mm is the ' dead zone ' for the detector and sensing is not possible over this region

Using equation (6 3) and differentiating with respect to h_1, to find the condition for occurrence of maxima we get the under mentioned relationship

$$d_2^{\ 2} = d_1^{\ 2} \left(\exp \left(2 / w(z)^2 \left(d_2^{\ 2} - d_1^{\ 2} \right) \right) \right) \tag{6 4}$$

$$(M^2 / r^2) x^4 - (2 M^2 / r) x^3 + (M^2 - (4/r^2)) x^2 + (4/r) x - 1 = 0 \tag{6 5}$$

where $x = (h - h_1)$, $M = (2 \ m / pi \ n_1 \ w_o^{\ 2})$, m is the wavelength of the light emitted by the source and w_o is the waist spot size of the beam

Equation (6 5) is a fourth order polynomial and we write a program in FORTRAN using NAG routine ' CO2AGF ' [2] to calculate the roots of the polynomial which gives us the condition for occurrence of the maxima

6.7 Reduction of Effect of Offset

In this chapter we have considered the offset which exists between the source and the detector and derived an expression to calculate power and coupling efficiency at the detector, taking it into account The response of an offseted detector was analysed An annular ring shaped detector was proposed which removes the need to introduce an offset Using this detector, an expression to calculate power and coupling efficiency at the detector was derived   The response of this detector was analysed and the conditions for occurrence of maxima in this case were derived

To reduce the effects of these lateral and angular misalignments on power coupling efficiency, we may use an array of photodiodes to detect the optical signal, instead of using a single photodiode [3] The detector array so designed may contain (2m+ 1) identical elements, where m is a positive integer We assume that the central photodiode m = 0 is perfectly aligned with the optical source The photocurrents from each photodiode are added together to form the net output signal

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TABLE 6.1

LIST OF DESIGN PARAMETERS SELECTED

1	Diameter of tube	23 mm
2	Height of tube	115 mm
3	Refractive index of liquid	1 33
4	Radius of detector	2 mm
5	Radius of source	1 mm
6	Wavelength of laser diode	670 nM
7	Waist spot size at give wavelength	100 microns
8	Output power of source	2 mW
9	Absorption coeff /mm at given wavelength	$7\ 6\ 10^{-3}$
10	Surface tension of liquid	$72\ 91\ 10^{-3}\ N/m^2$
11.	Angle of contact of liquid with solid	8 degrees
12	Density of liquid	$1000\ kg/m^3$
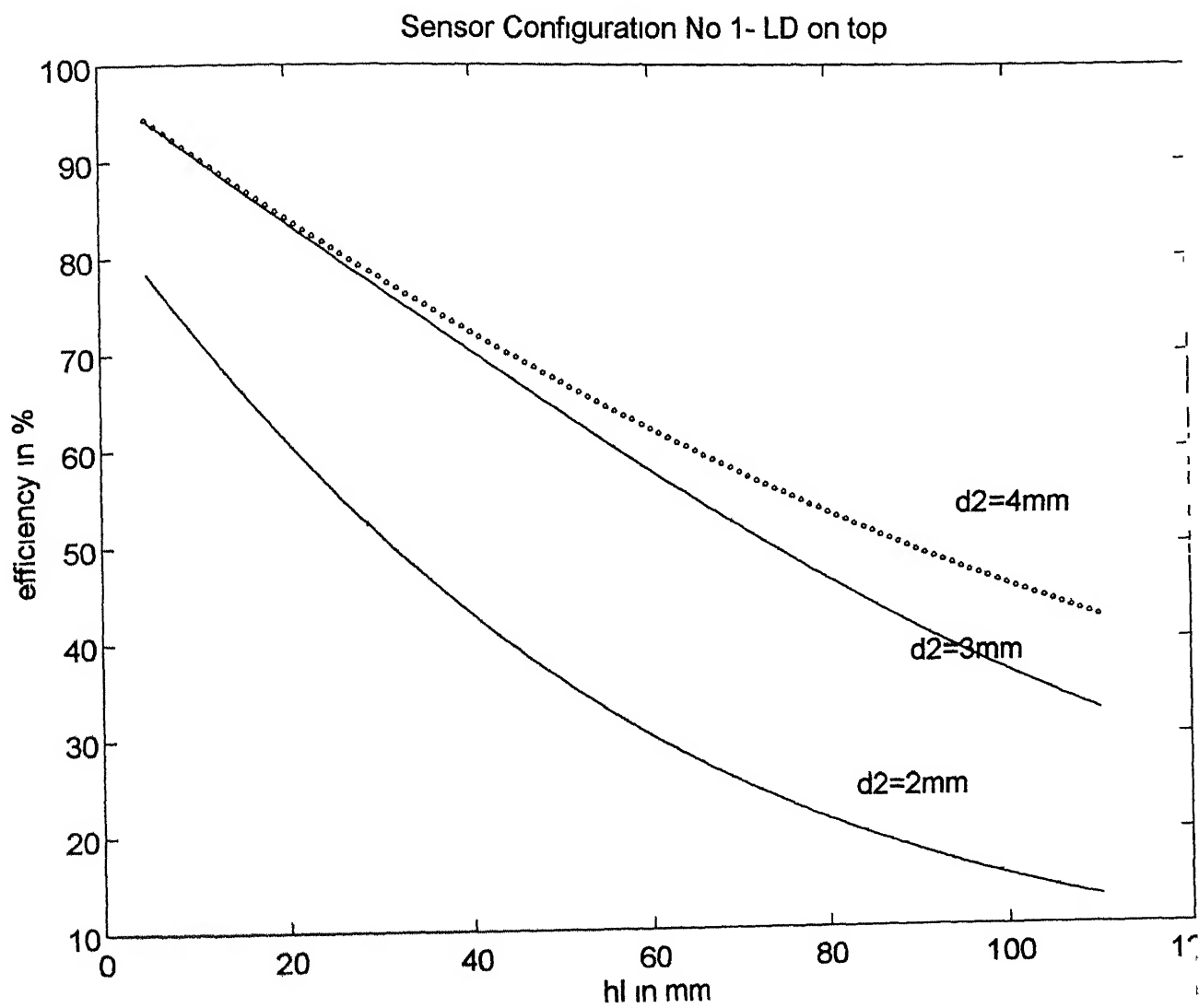
Fig 6.1 Coupling Eff vs Liq level, for variation in radius of detector
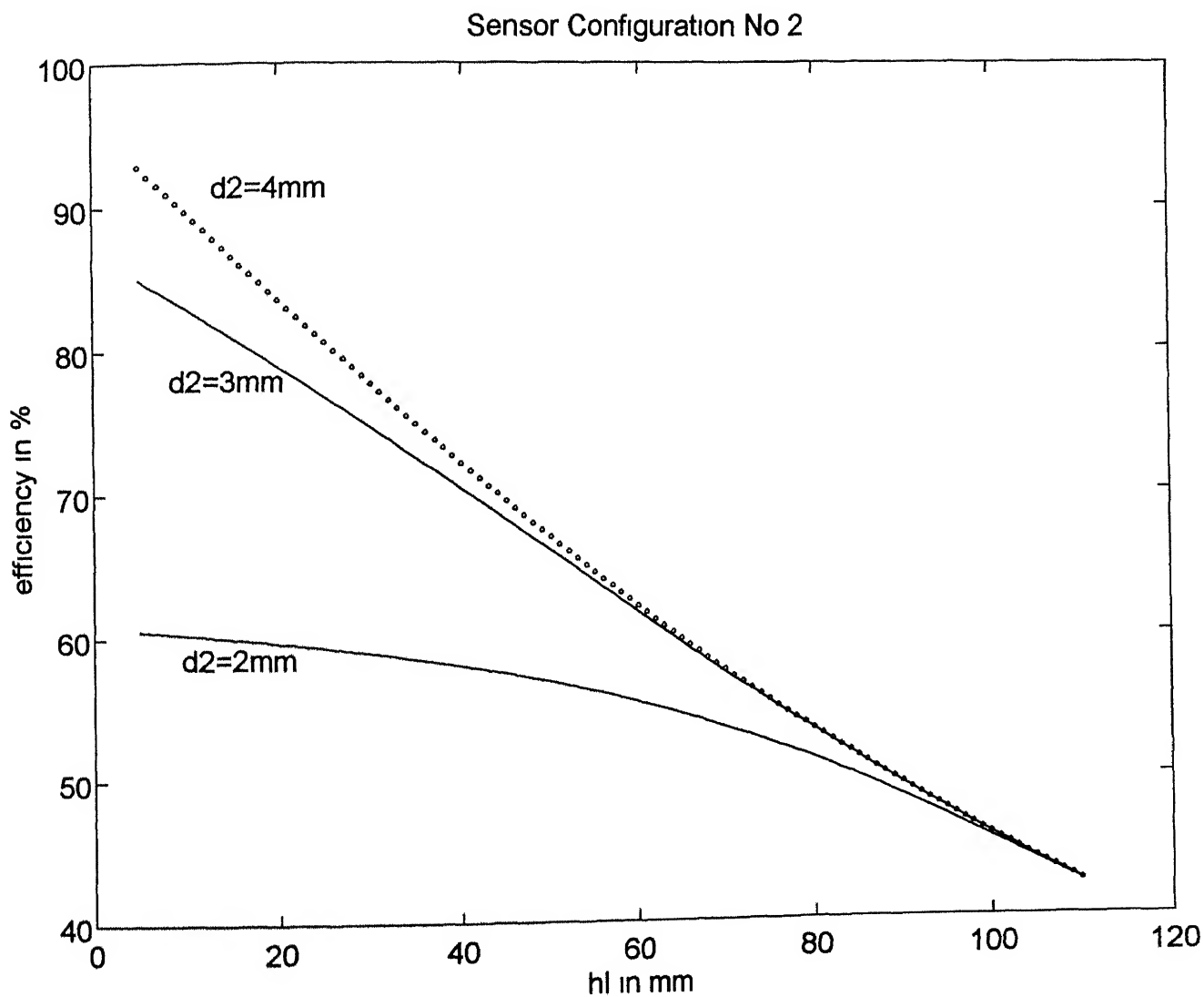
Fig 6 2 Coupling Eff vs Liq level, for variation in radius of detector
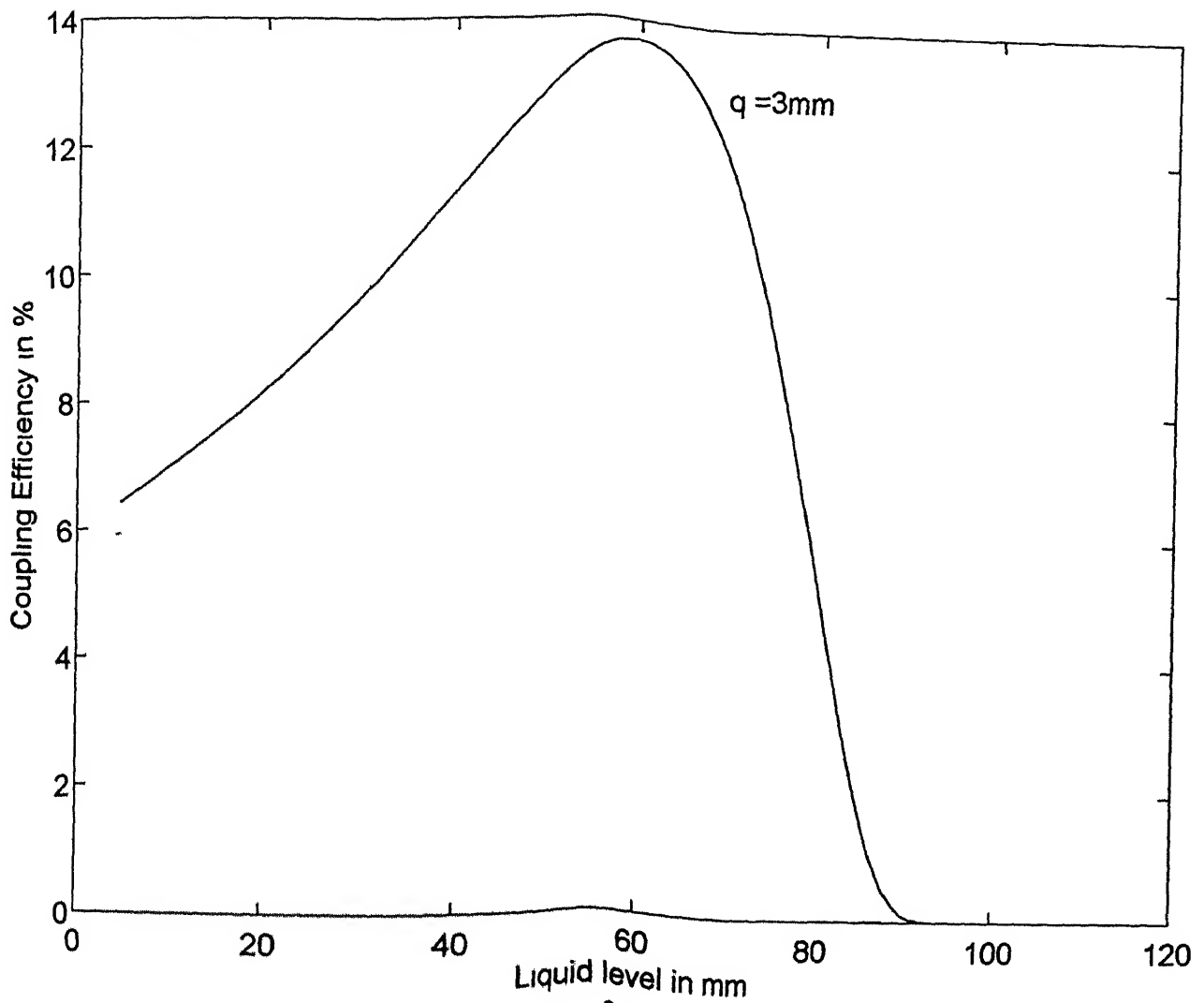
Fig.6.3 Coupling Eff vs Liq level for Sensor Configuration No.3, offset q = 3mm

73
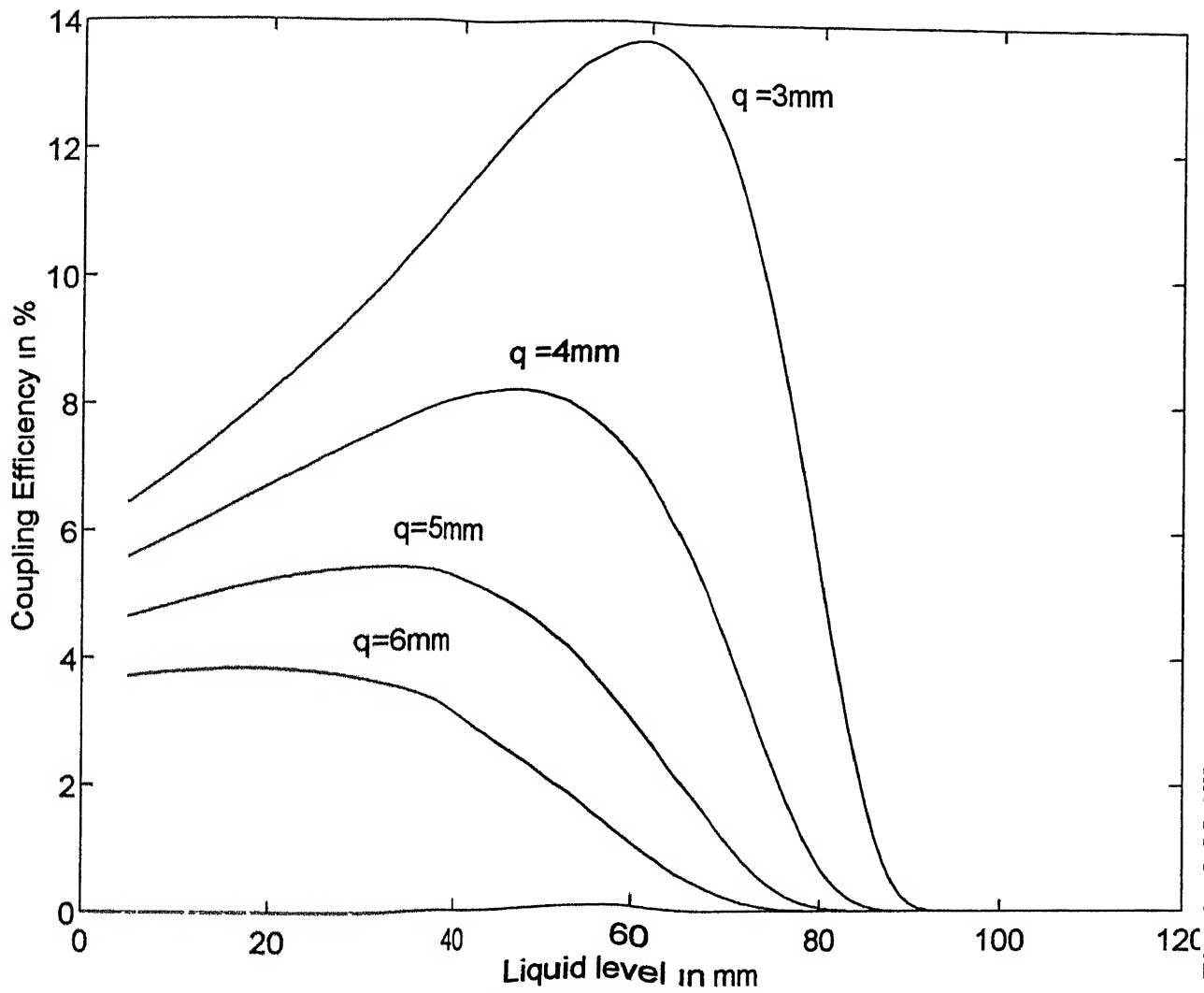
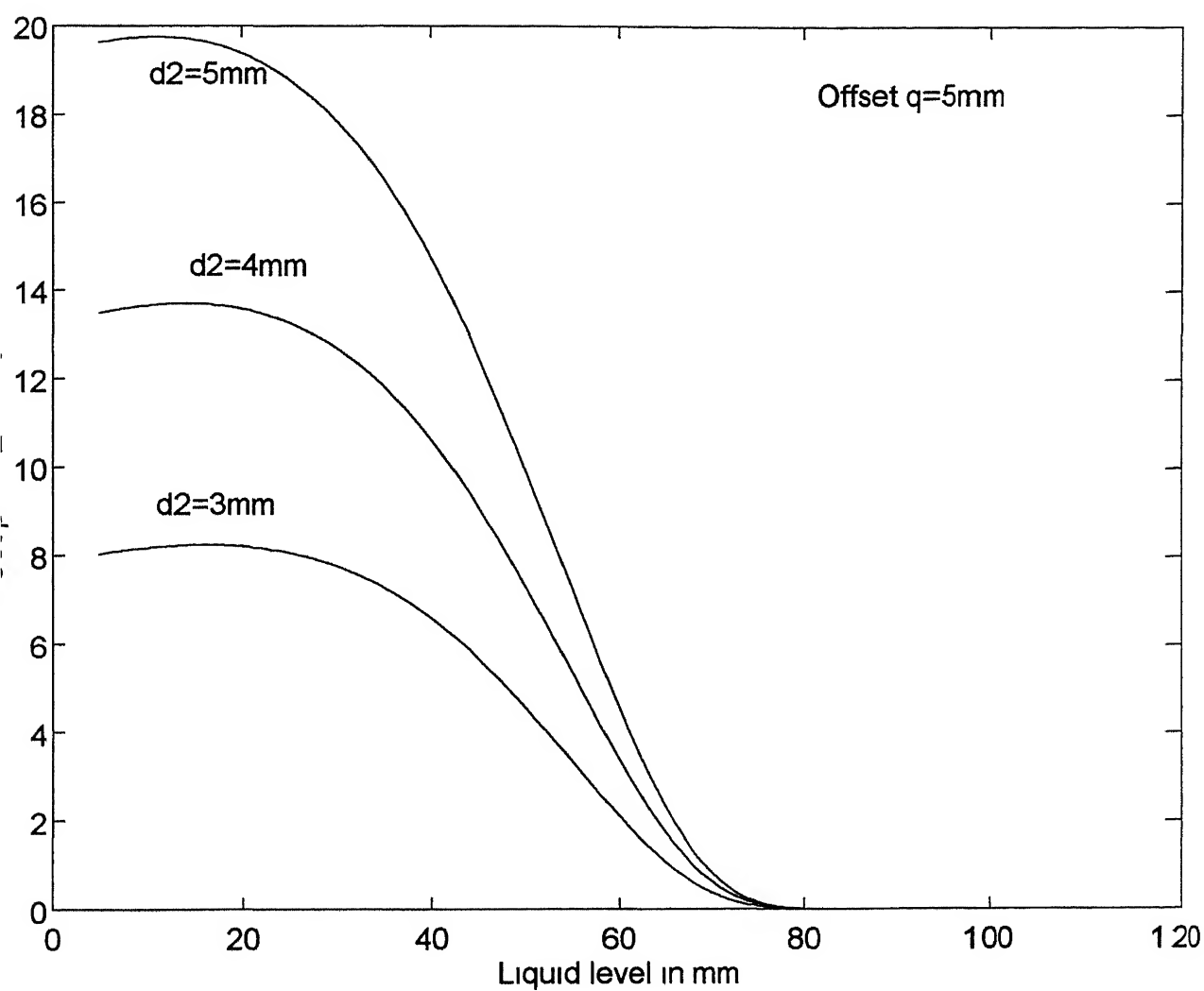Fig 6.4 Coupling Eff vs Liq level for variation in the offset q

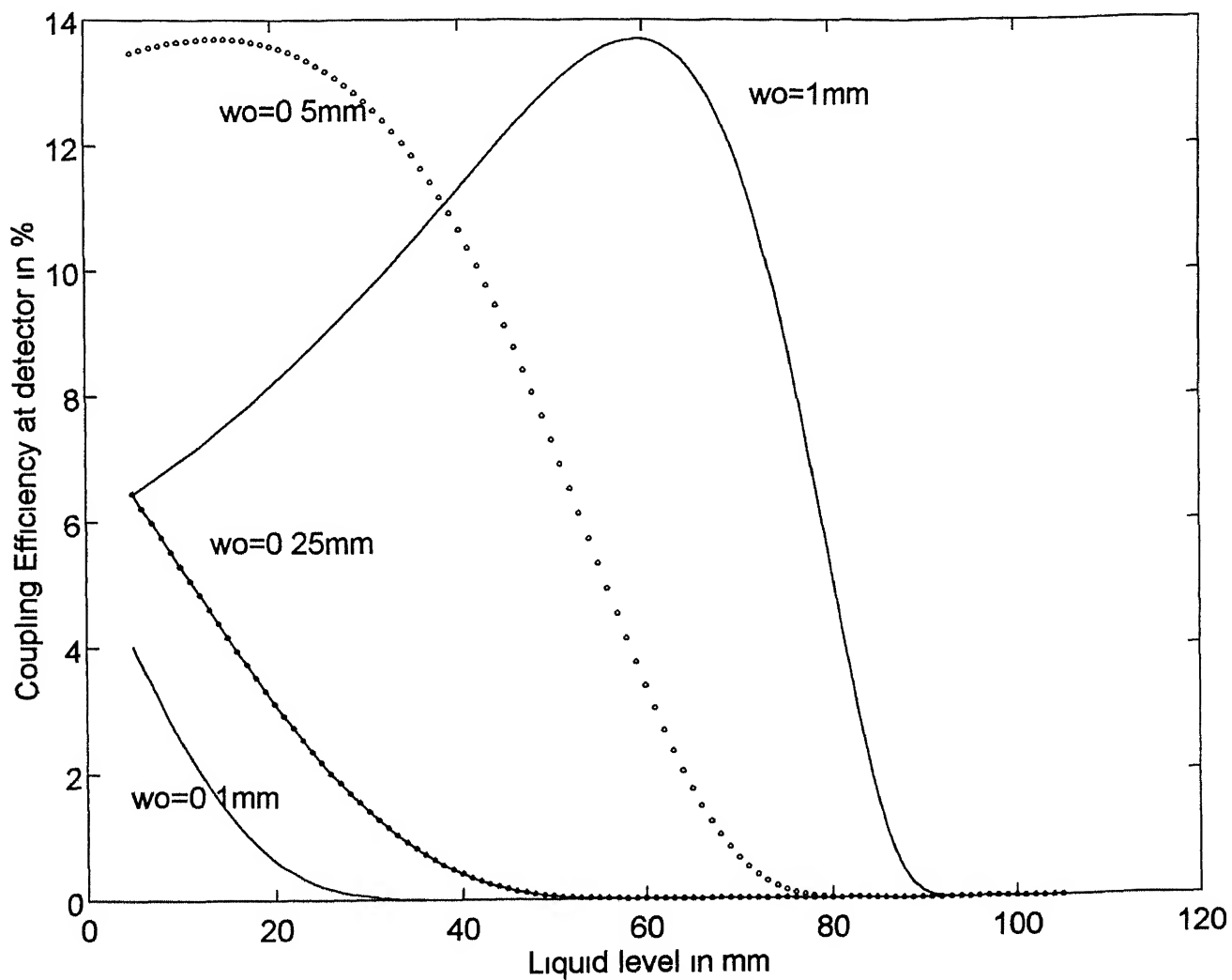Fig 6 5 Coupling Eff vs Liq level, for variation in radius of detector

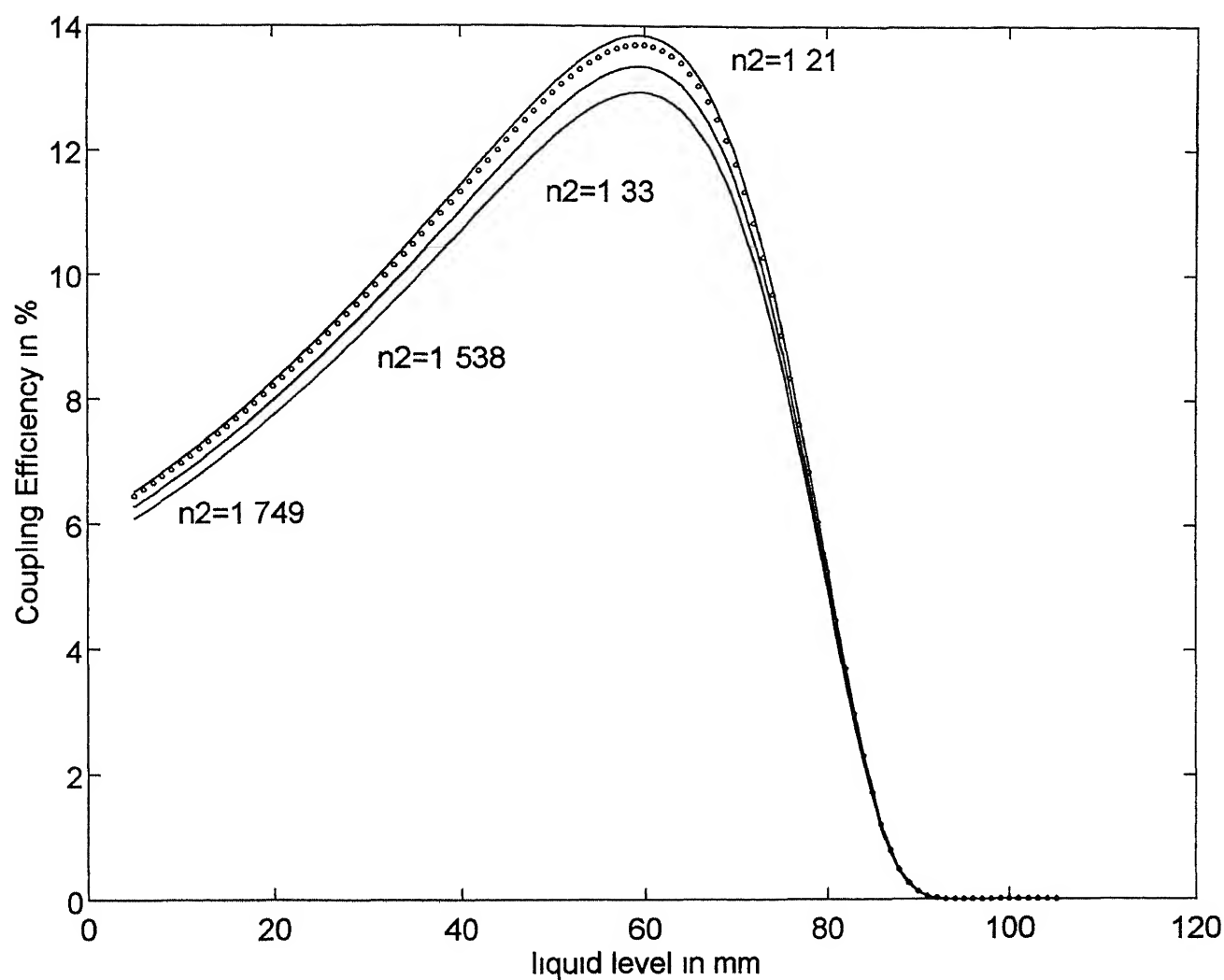Fig 6 6 Coupling Eff vs Liq level, for variation in min spot size

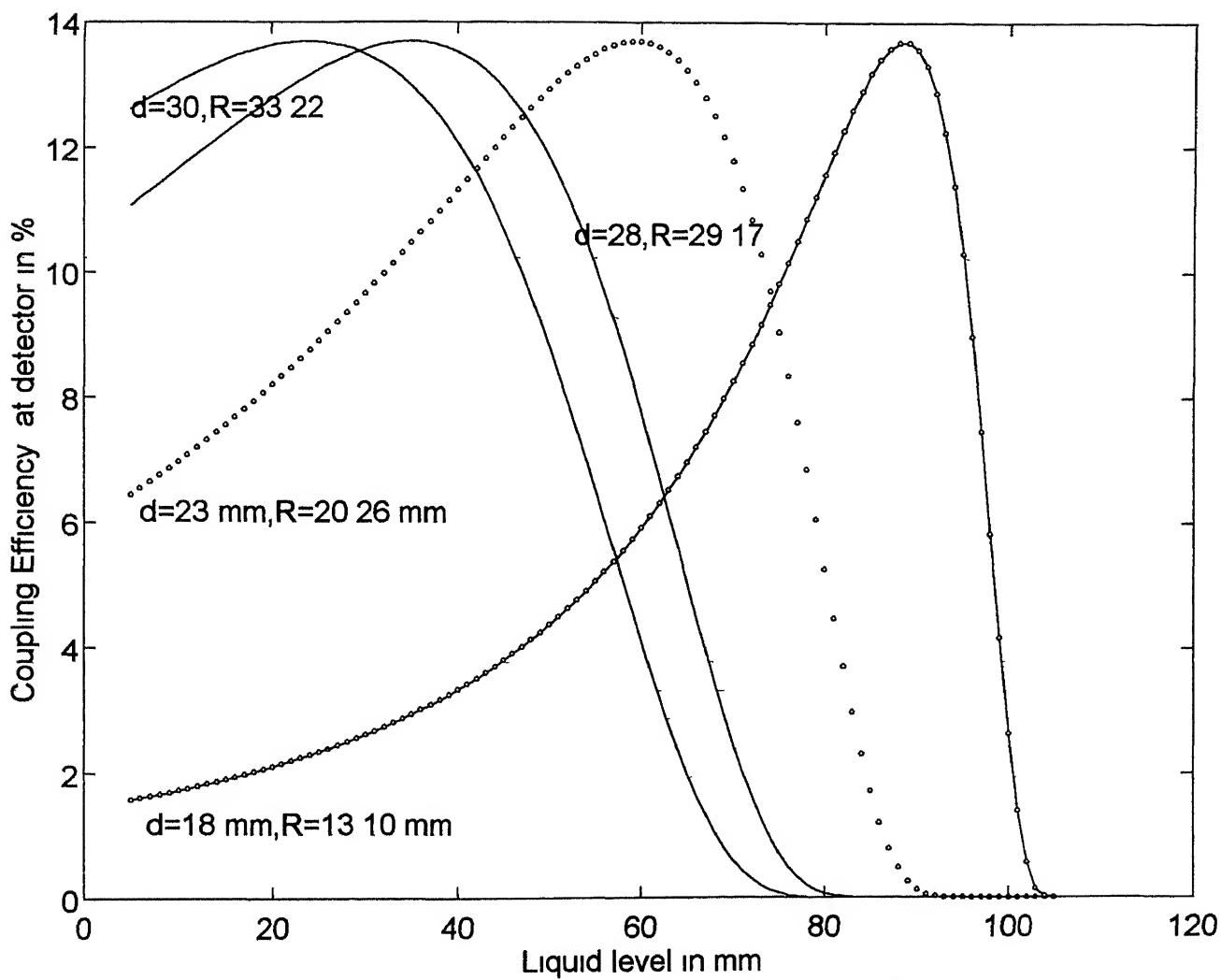Fig 6 7 Coupling Eff vs Liq Level, for variation in liq refractive index

Fig 6 8Coupling Eff vs Liq Level, for variation in diameter of tube
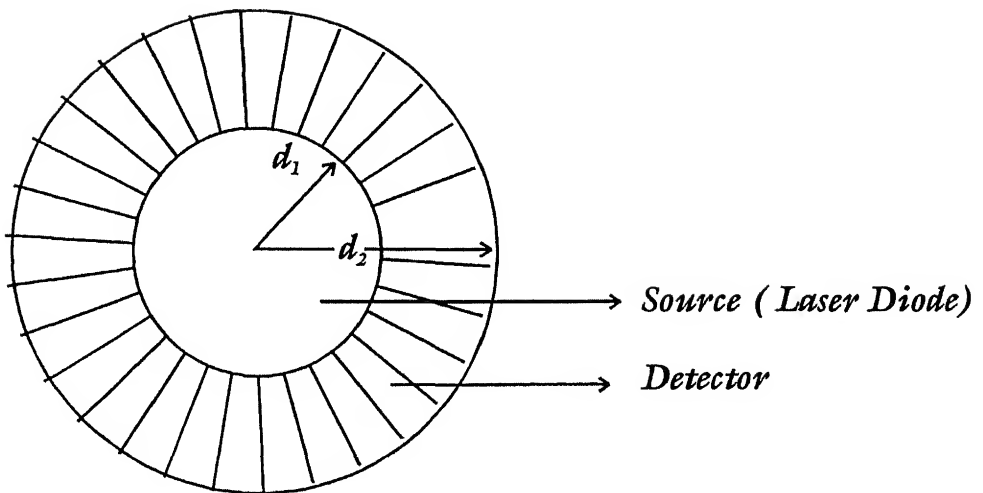
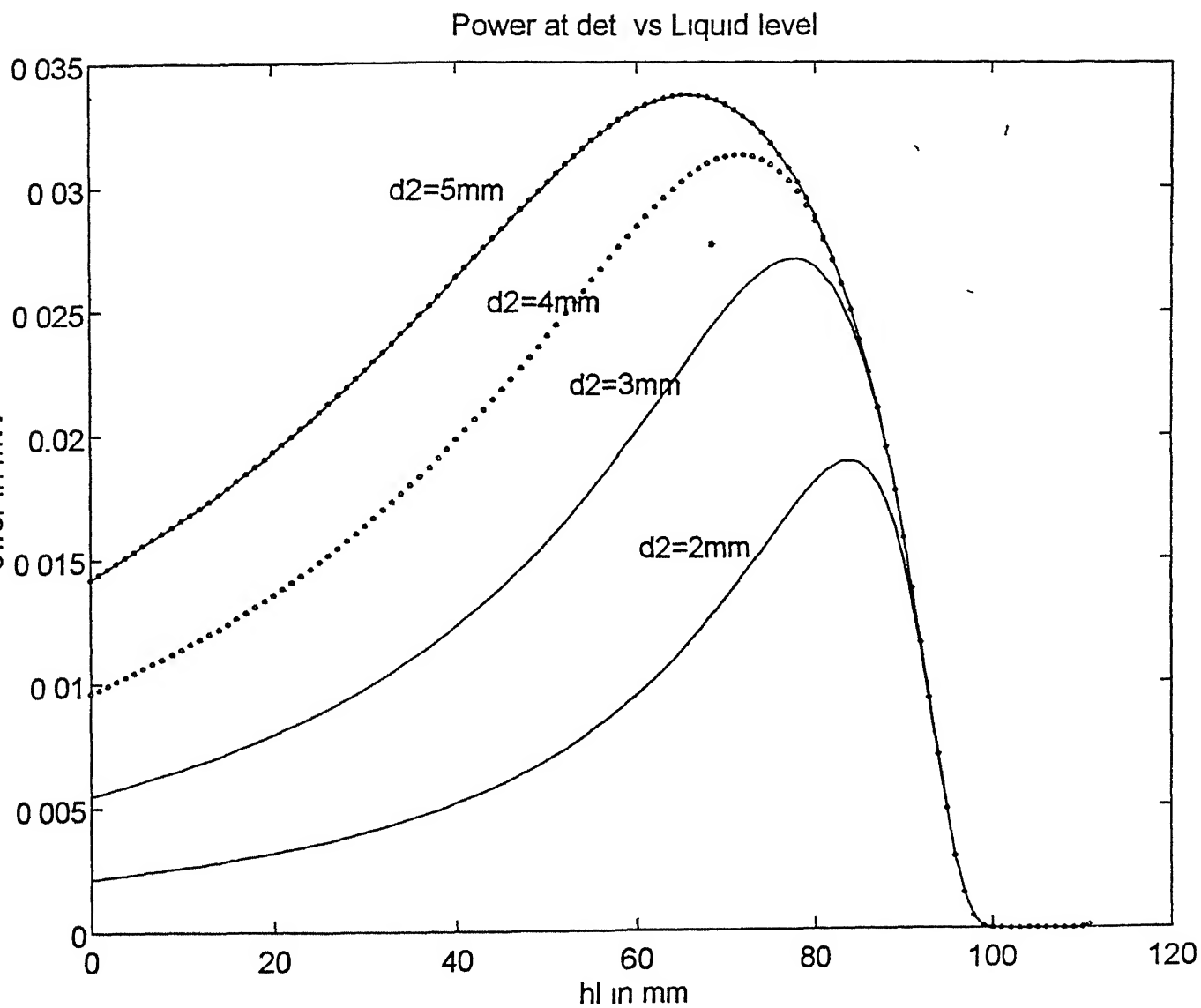Fig. 6.9 *An annular (ring shaped) detector*

Fig 610 Power vs Liq level, for variation in outer radius of ann det

CHAPTER 7

SCOPE FOR FUTURE WORK andCONCLUSION

7.1 Conclusions

The package design for a low cost liquid level optic sensor has been studied in detail using the geometric optic and physical optic considerations The expressions for the spot size at the detector and the power coupled to the detector, have been derived for the simple case of all the four possible configurations of our optical liquid level sensor A comparative analysis of the four configurations was carried out and a feasible configuration for our low cost optical sensor was selected and analyzed in detail

The design parameters were varied and the following were observed

The effect of various parameters on the sensor response are seen and analyzed for better understanding of the behaviour of the optical sensor It is seen that coupling efficiency increases with an increase in the radius of the detector, because larger area at detector is available for collection of power Thus one way to improve coupling efficiency in an optical sensor is by selecting a large size detector

(a)   It is also seen in configuration no 3, that power initially increases with increase in liquid level and then decreases after reaching a peak value because after a certain liquid level, when the light reflected from the liquid surface falls on the complete area of the detector, then maximum P_d and Eff are achieved After this stage, though there is no further increase in the area of the detector which receives light, yet the intensity of light falling per unit area decreases and thus P_d and Eff decrease and this is the region of back slope of the plot

The variation in the response of this sensor is uniform and both the front and the back slope can be utilised for sensing purpose However, when the front slope is used for sensing, the dead zone that occurs is different than the dead zone that would occur if the back slope is used for sensing

(b) The values of various design parameters for our optical liquid level sensor were selected after a detailed analysis and the list of the same is given at table 6 1

(c) The offseted detector has a dead zone beyond 85 mm and as such accurate level sensing is not possible from 85 mm to 105 mm

(d) The drawback of the offseted detector listed at srl (c) above can be overcome by using an annular detector ,which is able to sense upto 100 mm

(e) The annular detector is not prone to misalignment errors and is thus more reliable than the offseted detector

(f) The physical offset between the source and the detector for the reflective type of sensors has been incorporated in the calculations for the spot size, power and coupling efficiency It is seen that as offset increases, efficiency decreases as less power is being coupled to the detector because the detector falls partially within the cone of light reflected from the liquid surface

(g) In view of the nature of propagation and spread of the gaussian beam, in order to minimize reflections from the side walls, an ideal shape for the low cost optical sensor of configuration no 3 is a tube which increases in diameter on going from the top to the bottom of the tube
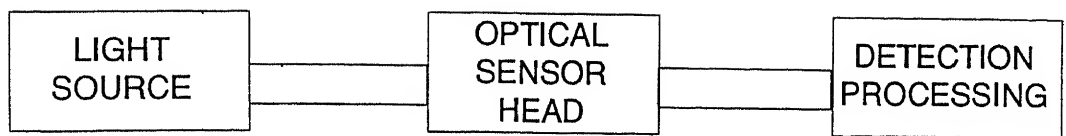
7 2 Scope for Future Work

7 2.1 Various Applications Possible In this thesis we have looked at a reflective optical sensor for a reflecting surface with a radius of curvature 'R' This work has a large application in automobile and aeronautical industry The same work can be used for measurement of various kinds of lateral displacement
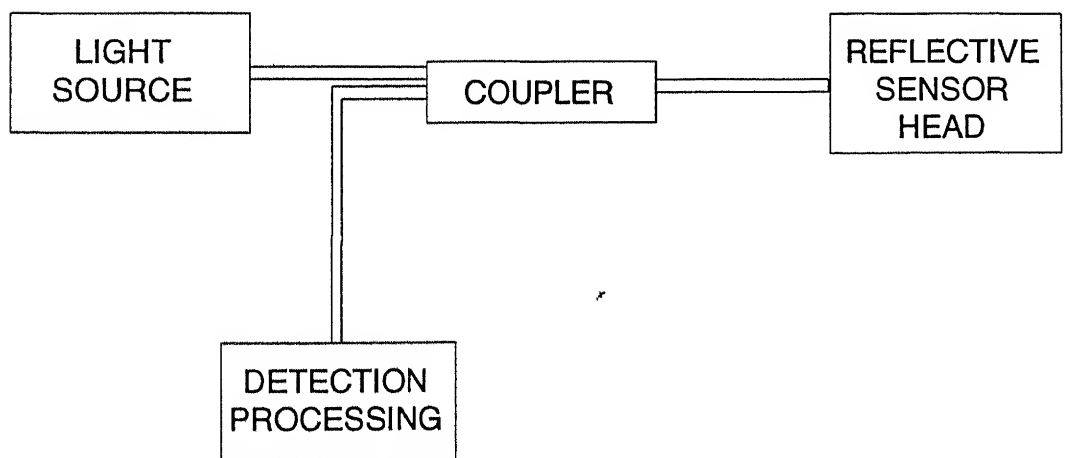
Based on the work done in this thesis, the transmissive type of sensor can be used to measure the refractive index of the liquid

Other than liquid level measurement, the work done in this thesis can be used for vibration measurement The light can be made incident on a reflecting diaphragm and the number of vibrations is equal to the frequency of change of the radius of curvature of the diaphragm, which can be measured The same principle can be extended for the design of sound intensity hydrophones and in SONAR applications

The same work can also be extended for various cylindrical objects having circular reflecting surfaces, thus shaft wear out can be measured using these principles

LIGHT
SOURCE

OPTICAL
SENSOR
HEAD

DETECTION
PROCESSING

(a) TRANSMISSIVE MODE

LIGHT
SOURCE

COUPLER

REFLECTIVE
SENSOR
HEAD

DETECTION
PROCESSING

(b) REFLECTIVE MODE

FIG. 7.1 Extrinsic Fiber Optic Sensors

EXPRESSION FOR SPOT SIZE AT DETECTOR FOR CONFIGURATION NO 1

In this configuration, the laser diode is at the top of the tube and the detector is at the bottom As shown in Fig (5 5), if some liquid of refractive index n2 partially fills up the gap of length z between the optical source and photodiode, then the optical beam will propagate partially through air (distance z - h) and partly through a liquid column of height h The light travelling from the top of the tube thus encounters a concave dielectric interface whose ray matrix in terms of A,B,C,D parameters [7]is given by

$$
\begin{bmatrix}
1 & 0 \\
\dfrac{(n2 - n1)}{n2\,R} & \dfrac{n1}{n2}
\end{bmatrix}
\tag{A 1}
$$

The detailed derivation of the above expression has been done in appendix B In the above expression, R is the radius of curvature of the liquid, n1 and n2 are the refractive indices of air and liquid respectively

The complex beam parameters at various planes are as under [5]

q1 - at plane 11' i e at the output of the laser diode

q2(-) - at plane 22' i.e above the air liquid interface (as viewed from the top of the tube)

q2(+) - at plane 22' i e below the air liquid interface (as viewed from the top of the tube)

q3 - at plane 33' i e at the input end of the detector

At plane 11' that is at source (z =0), the complex beam parameter q1 is given by [6]

$$
1/q1 = - j\, \lambda \,/\, n1\, \pi\, w(z)^2
\tag{A 2}
$$

where wo is the size of gaussian beam measured at z =0 The transformed beam parameter q2(-) just to the left of the air liquid interface is given by q2(-) = q1 + (z - h) The beam parameter q2(+), just below the air liquid interface is given by

$$
q2(+) = \left[\frac{A\,q2(-) + C}{B\,q2(-) + D} \right]
\tag{A 3}
$$

where A B,C,D are the elements of the ray matrix given by expression (A 1)

For the ease of computation we will denote $M = n1 \pi w(z)^2 / \lambda$ (A 4)

and $Q = (n2-n1)/n2R$ (A 5)

thus $q2(+) = \left[\dfrac{jM + (z-h)}{Q(jM + z - h) + (n1/n2)} \right]$

Finally the beam parameter q3 at the liquid detector interface is given by $q3 = (q2(+) + h)$

Thus $q3 = \left[\dfrac{jM + (z-h) + Qh(jM + z - h) + h(n1/n2)}{Q(jM + z - h) + (n1/n2)} \right]$ (A 6)

Also ,q3 is related to the beam spot size w3 and radius of curvature of the beam R3 , through the equation

$1/q3 = 1/R3 \quad - \; j \lambda / n2 \pi w3^2$ (A 7)

From equations (A 6) and (A 7),comparing the coefficients of the imaginary terms , the expression for beam spot size at plane 33' given by

$w3 = wo \sqrt{(1 + (n2 - n1)h / n2 R)^2 + (g \lambda / n1 \pi wo)^2}$ (A 8)

where $g = ((n2/n1) h / n2R + 1)(z - h) + (n1 / n2) h$

RAY MATRIX FOR A CONCAVE DIELECTRIC INTERFACE

1 Shown in fig B 1 , θ_1 and θ_2 are the angles made by the incident and the refracted rays with the normal to the surface

2 The following conventions are followed

    (a) Light travels from right to left

    (b) Angle is positive if upward sloped

    (c) Height is positive (i e $+\backslash$) if measured above the optical axis

    (d) Distances along optical axis are measured with respect to the vertices

    (e) Distance travelled along direction of light is positive

By snells law , $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Thus $n_1\,\theta_1 \approx n_2\,\theta_2$

$$\left|\theta_1'\right| = |\psi| - \alpha_1 \qquad\qquad \text{where } \psi = \tan^{-1} x_1/R \approx x_1/R$$

Thus, $\left|\theta_1\right| = (-x_1/R\ ) - \alpha_1$

$$\theta_2 = |\alpha_2| + |\psi|$$

$$\theta_2 = -\alpha_2 - \psi \qquad (\text{because of sign convention})$$

But $n_1\,\theta_1 = n_2\,\theta_2$

$$n_1\,(-\psi - \alpha_1) = n_2\,(-\alpha_2 - \psi)$$

$$\Rightarrow n_2\,\alpha_2 = n_1 + (n_1 - n_2)\psi$$

$$\Rightarrow \alpha_2 = ((n_1 - n_2)/n_2)(-x_1/R) + (n_1/n_2)\alpha_1$$

$$= ((n_2 - n_1)/n_2 R)x_1 + (n_1/n_2)\alpha_1$$

$\& x_2 = 1 \ x_1 + 0 \ \alpha_1$

Thus $\begin{bmatrix} x_2 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ (n_2 - n_1)/n_2 R & (n_1/n_2) \end{bmatrix} \begin{bmatrix} x_1 \\ \alpha_1 \end{bmatrix}$

Thus the ray matrix is given by the expression $\begin{bmatrix} 1 & 0 \\ \dfrac{(n2 - n1)}{n2 \, R} & \dfrac{n1}{n2} \end{bmatrix}$
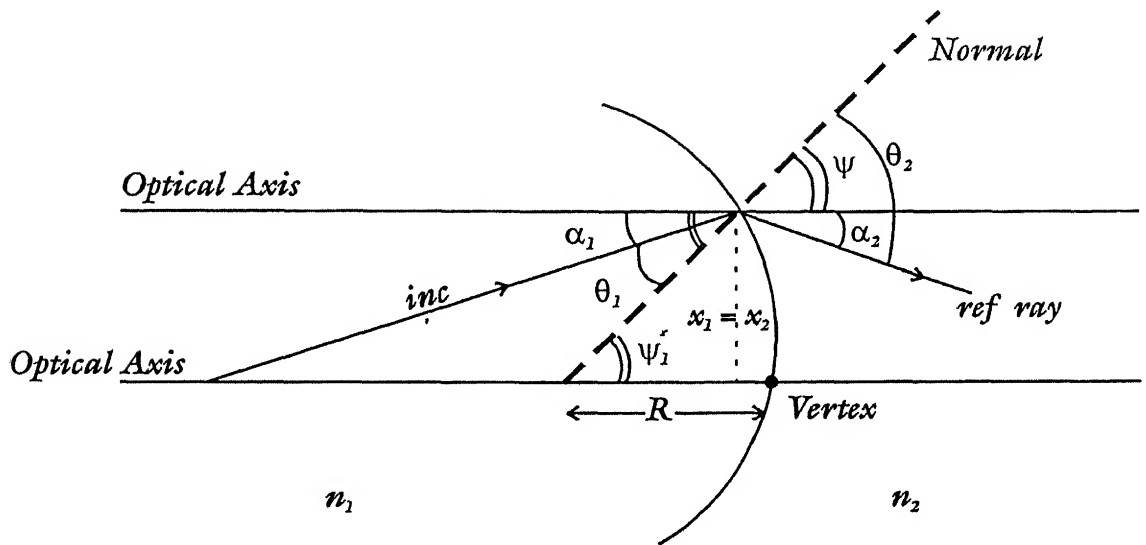
Fig. A.1 Concave spherical dielectric interface

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